PENNSYLVANIAN DEPOSITIONAL SYSTEMS IN NORTH-CENTRAL TEXAS

A GUIDE FOR INTERPRETING TERRIGENOUS CLASTIC FACIES IN A CRATONIC BASIN

BY
L.F. BROWN, JR., A.W. CLEAVES, II,
AND A.W. ERXLEBEN

GUIDEBOOK NUMBER 14

BUREAU OF ECONOMIC GEOLOGY
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W. L. FISHER, DIRECTOR
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PREFACE

The geometry, internal character, and spatial distribution of terrigenous clastic facies provide critical insight into the nature of basin-fill deposits containing important mineral and energy resources. Use of many other land and water resources, not to mention many factors of potential environmental significance, is strongly dictated by the three-dimensional properties of terrigenous clastic deposits. Development of the capability to predict quantitatively the distribution and critical properties of earth resources within sedimentary rocks requires a lithogenetic approach in which depositional processes and sedimentary environments can be inferred with increasing accuracy. Through facies analyses of basin fill using modern analogs, it is possible to assemble with increasing accuracy those facies that are linked genetically by process and environment. These three-dimensional assemblages of genetically linked facies have been called *depositional systems* (Fisher and McGowen, 1967), and they are analogous to and are interpreted from the character of their modern counterparts; e.g., fluvial, deltaic, slope, fan, or barrier island systems. An ancient delta system, therefore, is the stratigraphic counterpart or preserved record of deposition within the myriad environments that constitute a modern delta.

Just as facies may be assembled genetically into systems, so can systems be assembled genetically to provide insight into the nature and sequence of sedimentary fill deposited within structurally evolving basins. As a basin evolves structurally, the character and spatial relations of depositional systems change in concert with tectonic requirements. Of course, determining the history of basin development from the anatomy of its sedimentary fill is a goal of most geologists.

The Middle and Upper Pennsylvanian rocks of North- and West-Central Texas represent a considerable segment of basin history, enough perhaps so that one can begin to grasp the effect of regional tectonic evolution on the nature and distribution of principal depositional systems. The geologist must begin with the interpretation of the fundamentals—that is, the interpretation of individual facies from outcrop, core samples, or E-logs. Then he can begin to understand the history of a basin or the history of a smaller segment of the basin.

This field guide is designed to provide an opportunity to observe a variety of facies that are the fundamental blocks with which principal depositional systems have been fabricated. Available data is provided and a genetic interpretation is proposed. Although the validity of the interpretation may be questioned, it is anticipated that the interpretation will focus attention on the problems and limitations of facies interpretation in basin analysis.

The principal goal of this field guide is to examine the genetic significance of a variety of common terrigenous clastic facies by attempting to apply a holistic or integrated approach utilizing all available methods and data. Principal use has been made of primary evidence such as data on the regional stratigraphic framework, geologic maps, maps of sandstone bodies, geometry of facies, interpretation of vertical sequences, development of facies tracts, tracing shifts in flow regime from sedimentary structures, paleoecologic evidence, petrographic character of the rocks, and information from other methods of study. Surface and subsurface data are integrated, as is local and regional structural information.

The field guide presents (1) a tectonic and depositional synthesis to provide a regional perspective; (2) a brief summary of models of the more common depositional systems; (3) a synthesis of principal stratigraphic units to be examined (Strawn, Canyon, and Cisco Groups); and (4) field localities selected to provide a spectrum of fluvial, deltaic, and strike systems for examination.

It is impossible to credit everyone who has contributed to the studies in North- and West-Central Texas, much less the workers who, over the decades, have developed so many of the ideas that are used today in facies analysis; specific contributions are cited throughout the guidebook. A number of people, however, should be individually recognized because of the special impact of their ideas and their oral and published contributions: W. L. Fisher, Director, and J. H. McGowen, Bureau of Economic Geology; A. J. Scott, Department of Geological Sciences, The University of Texas at Austin; W. L. Galloway, Continental Oil Company, Ponca City, Oklahoma; David E. Frazier, Esso Production Research Corporation, Houston; Rufus LeBlanc, Shell Development Company, Houston; and Alan Donaldson, Department of Geology, University of West Virginia, Morgantown. Elizabeth T. Moore, Kelley Kennedy, and Fannie M. Sellingsloh expeditiously edited and processed this guidebook; cartography was under the direction of James W. Macon; and research assistance during manuscript preparation was supplied by Terrence O'Donnell and Preston Walters.

—*L. F. Brown, Jr.*

PENNSYLVANIAN ROCKS OF NORTH-CENTRAL TEXAS: AN INTRODUCTION

L. F. Brown, Jr.[1]

The Pennsylvanian and Permian rocks of North- and West-Central Texas (fig. 1) have been economically important for more than 80 years. Coal, oil, gas, clay, and limestone have been principal mineral and energy resources produced in the region. Copper in Permian red beds will probably become economic in the near future. Coal was mined from deltaic and fluvial facies in the Strawn, Canyon, and Cisco Groups (fig. 2) during the two decades before and after the turn of the century. The region has been an important oil and gas province since the early World War I discoveries at Ranger and Breckenridge, developed on local structures on the Eastern Shelf (fig. 3). Many of the early pay zones in North-Central Texas are Strawn and Cisco fluvial-deltaic sandstone facies. Strawn, Canyon, and Cisco carbonate bank-reef facies later became important reservoirs, along with growing interest in Cisco slope facies. Early Pennsylvanian Caddo-Marble Falls platform carbonates have been exploration targets for more than 50 years.

Five ceramic and clay products companies, concentrated near Mineral Wells, utilize deltaic clays in the region. The Chico Ridge limestone bank (Canyon Group) at Bridgeport is the principal source of limestone aggregate for the Fort Worth-Dallas metropolitan area.

Because of its economic importance, the geology of the region has been of interest to hundreds of geologists. The reader is referred to comprehensive bibliographies of Texas geology (Sellards and others, 1932; Girard, 1959; Moore and Brown, 1972) for further sources of information, such as theses, maps, and reports.

Several studies in North- and West-Central Texas during the past 20 years have focused on facies interpretation and regional basinal development. These include workers such as Cheney and Goss (1952); Turner (1957); Van Siclen (1959); Wermund and Jenkins (1969, 1970); Brown (1969c); and Galloway and Brown (1972, 1973). These reports have begun to provide a regional view of the sedimentary basins. All recent studies are based on the early fundamental work of Dumble (1890), Tarr (1890), Cummins (1891), Drake (1893), Plummer and Moore (1921) and Lee and others (1938).

[1]Bureau of Economic Geology, The University of Texas at Austin

TECTONIC AND DEPOSITIONAL HISTORY

The geologic history of North- and West-Central Texas is closely tied to the tectonic development of the Fort Worth (foreland) Basin, the eastern flank of the Midland Basin, and the Red River uplift—southern Oklahoma Mountains (fig. 1). The structural evolution of these basins and associated tectonic elements determined to a great extent the nature and distribution of the principal basin-filling depositional systems.

Based on approximately 5,000 wells, extensive studies of the Strawn, Canyon, and Cisco Groups in outcrop (fig. 4), as well as on published information by Turner (1957), the general evolution of basin tectonics and depositional systems has been synthesized (fig. 5).

Fort Worth Basin-Concho Platform

Early and Middle Paleozoic deposition in the region was principally restricted to (1) carbonate platform facies on the Early-Middle Paleozoic Concho Platform (Cheney and Goss, 1952), and (2) starved-basin deposition in the Ouachita geosyncline. The eastward platform-to-basin transition (fig. 5) in Ordovician facies, such as Ellenburger and Simpson-Viola, is poorly understood because of structural complications such as overthrusting and the depth of burial.

Beginning with Late Mississippian and Early Pennsylvanian structural activity in the Ouachita geosyncline, the Fort Worth foreland basin became well defined (fig. 5). Late Mississippian and Early Pennsylvanian platform and shelf-edge carbonate environments (Marble Falls, Big Saline, Comyn, and Caddo) contemporaneously dominated the Concho Platform. Late Mississippian and Early Pennsylvanian shelf edges faced generally eastward toward the rapidly subsiding, but not necessarily deep, Fort Worth Basin. Generally equivalent, westward prograding terrigenous clastic wedges (Atoka Group) entered the basin along a high-gradient paleoslope from the Ouachita foldbelt to the east. Thousands of feet of Atoka mudstones of probable fan-delta and related slope origin graded westward and basinward into the thin, relatively starved basinal Smithwick facies. Basinal Smithwick shales and siltstones intertongue west-

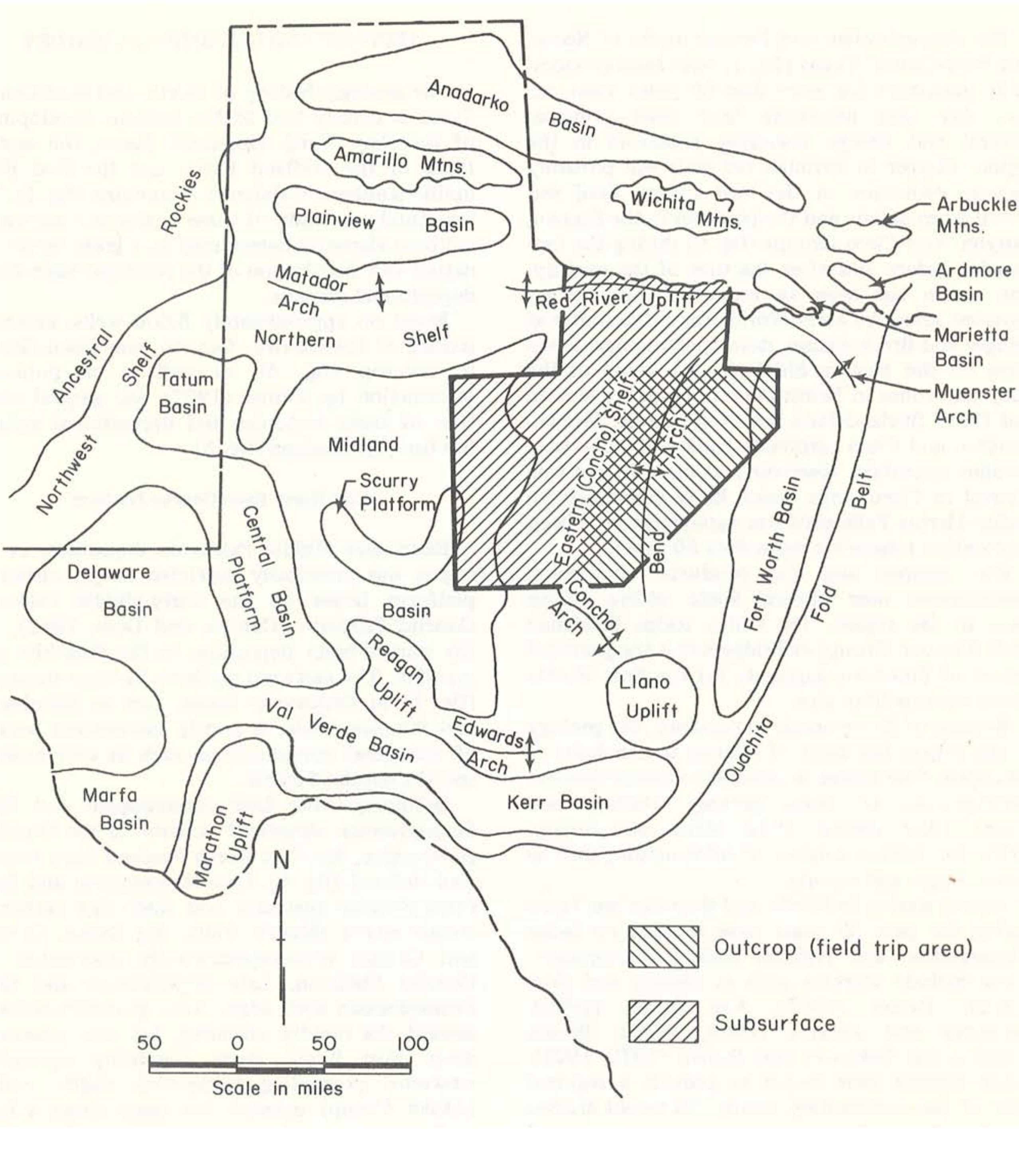


Figure 1. Index map showing structural setting of field trip and adjacent subsurface study area. Modified from Wermund and Jenkins (1969); published with permission, Dallas Geological Society.

System	Series	Group	FORMATION	MEMBER OR INFORMAL UNITS	FIELD LOCALITY	FACIES
PERMIAN / PENNSYLVANIAN SYSTEM	WOLFCAMP / VIRGIL SERIES	CISCO GROUP	HARPERSVILLE FORMATION	Saddle Creek Limestone Coal Unnamed sandstone Lake Cisco Sandstone Coal Crystal Fall Limestone Breckenridge Limestone	10 15 11 14, K	10 Delta-flank bay, marine transgression 15 Point bar 11 Point bar, braided, valley-fill 14 Brackish lagoon, bay K Strike-fed beach or berm
PENNSYLVANIAN SYSTEM	VIRGIL SERIES	CISCO GROUP	THRIFTY AND GRAHAM FORMATIONS (UNDIVIDED)	Blach Ranch Limestone Unnamed sandstone Ivan Limestone Avis Sandstone Unnamed limestone Wayland Shale Gunsight Limestone Necessity Shale Unnamed sandstone Unnamed sandstone Bunger Limestone Gonzales Creek Member limestone, sandstone, shale Finis Shale	G, H 9, I 13 12	G Channel-mouth bar, delta plain H Crevasse splay, interdistributary bay 9 Delta front, distributary-mouth bar, growth fault I Prodelta, distal delta front, slump structures 13 Confined valley-fill 12 Distributary channel-fill, intensively contorted, interdistributary bay
PENNSYLVANIAN SYSTEM	MISSOURI SERIES	CANYON GROUP	HOME CREEK LIMESTONE	Kisinger Sandstone	J	J Valley-fill conglomerate
PENNSYLVANIAN SYSTEM	MISSOURI SERIES	CANYON GROUP	COLONY CREEK SHALE	Unnamed sandstone	A	A Distal distributary channel-fill contemporaneous faults, mud-filled channel
PENNSYLVANIAN SYSTEM	MISSOURI SERIES	CANYON GROUP	RANGER LIMESTONE			2 Delta front, distributary-mouth bar, distributary channel-fill, bay-lagoon carbonate
PENNSYLVANIAN SYSTEM	MISSOURI SERIES	CANYON GROUP	PLACID SHALE	Unnamed sandstone	2, 3,	3 Distributary channel-fill, contemporaneous faults, load structures
PENNSYLVANIAN SYSTEM	MISSOURI SERIES	CANYON GROUP	WINCHELL = CHICO RIDGE LIMESTONE	Devil's Den Limestone	F	
PENNSYLVANIAN SYSTEM	MISSOURI SERIES	CANYON GROUP	WOLF MOUNTAIN SHALE	Unnamed sandstone Rock Hill Limestone Lake Bridgeport Shale Unnamed sandstone	4, 8, B 1	F Tidal channel, shoreface 4 Distributary channel, delta front, marine reworked
PENNSYLVANIAN SYSTEM	MISSOURI SERIES	CANYON GROUP	PALO PINTO FORMATION	Wiles Limestone = Willow Point Limestone Bridgeport Coal Oran Sandstone Unnamed limestone Wynn Limestone		8 Distributary-mouth bar, distributary channel-fill B Massive delta front-distributary channel-fill, intensive slumping
PENNSYLVANIAN SYSTEM	MISSOURI / DES MOINES SERIES	STRAWN GROUP	MINERAL WELLS FORMATION	Keechi Creek Shale Turkey Creek Sandstone Salesville Shale Unnamed sandstone Dog Bend Limestone Lake Pinto Sandstone East Mountain Shale Village Bend Limestone Unnamed sandstone Hog Mountain Sandstone		1 Distal delta front, intensively deformed by submarine slumping
PENNSYLVANIAN SYSTEM	DES MOINES SERIES	STRAWN GROUP	BRAZOS RIVER FORMATION		C, D, E	C, D Delta front, extensively marine reworked E Valley fill conglomerate
PENNSYLVANIAN SYSTEM	DES MOINES SERIES	STRAWN GROUP	MINGUS FORMATION	Thurber Coal Unnamed sandstone Goen Limestone Dobbs Valley Sandstone Santo Limestone	7 5, 6	7 Interdistributary bay, small distributary channel-fill, delta plain, impure coal
PENNSYLVANIAN SYSTEM	DES MOINES SERIES	STRAWN GROUP	GRINDSTONE CREEK FORMATION	Buck Creek Sandstone Brannon Bridge Limestone		5 Delta front, prodelta, growth faults, submarine slumps
PENNSYLVANIAN SYSTEM	DES MOINES SERIES	STRAWN GROUP	LAZY BEND FORMATION	Steussy Shale Meek Bend Limestone Hill's Creek Shale		6 Distributary channel-fill

Figure 2. Stratigraphic position and genetic interpretation of facies observed at field localities.

ward with shelf-edge carbonates. As Atoka clastic wedges built westward under gradually diminished but westward-shifting basinal subsidence, the shelf edges of the Concho Platform carbonates retreated westward in a series of progressive "back steps," intertonguing in all places with the advancing Smithwick facies (fig. 5). Coarse gravel facies of the Atoka fan deltas reached the western flank of the Fort Worth Basin late in the waning stages of Atoka deposition. Facies within the Fort Worth Basin, both terrigenous clastic and carbonate, exhibit an unusually high degree of time-transgression. A westward to northwestward shift in basin axis, along with variable rates of subsidence and sediment supply, are principal factors controlling the westward shift of environments.

Eastern Shelf-Midland Basin

Decreased subsidence in the Fort Worth Basin and diminishing Atoka clastic input marked deceleration of Ouachita orogenic activity.

By the time of early Desmoines deposition (Strawn Group), the Ouachita sediment supply had diminished and Fort Worth Basin subsidence was significantly reduced. During early Strawn deposition, terrigenous clastics gradually assumed a deltaic character with lower paleogradients and a very shallow basin. During middle Strawn deposition, fluvial-deltaic systems overlapped the shelf-edge carbonate facies (Caddo) and began several cycles of extensive progradation westward across the Concho Platform (fig. 5). Smithwick prodelta-basinal facies were deposited in the path of the delta systems. During late Strawn deposition, delta-fluvial sedimentation continued as the Concho Platform underwent a gradual westward tilting and increased subsidence in response to accelerated development of the Midland Basin. Even though the stability of the Concho Platform decreased near the end of Strawn deposition, this structurally positive element still provided support for numerous Upper Strawn and Canyon Group reef and limestone banks, as well as for initiation of the high-relief shelf edges that later characterized the Eastern Shelf during deposition of the Cisco Group.

Coincident with Midland Basin subsidence, regional upwarping occurred in the Ouachita foldbelt and the eastern flank of the Fort Worth Basin; the hinge or axis of rotation between the subsiding Midland Basin and the gradually rising Fort Worth Basin defines the present Bend Flexure or Arch (figs. 1, 5). Uplift of the eastern part of the Fort Worth Basin, with consequent erosion of eastern Atoka fan-delta facies, provided a significant second-cycle supply of sediments to Strawn deltas. As the elevation of source areas was lowered by erosion and paleogradients were diminished, less terrigenous sediment reached the coastline. Extensive and long-lived carbonate-bank and reef systems then began to develop on the stable platforms provided by abandoned Strawn deltaic clastics. As the Midland Basin continued to subside, many reefs or banks grew vertically to maintain the necessary shallow-water environment. Trends of atoll-like limestone bodies that parallel the basin margin grew throughout much of the uppermost Pennsylvanian, but they are most common in the Canyon Group. Some of the carbonate banks, growing on structurally positive trends of the Eastern Shelf, extended upslope to the present outcrop area where they intertongued with Canyon deltaic systems. Although Canyon deltas prograded extensively during three principal deltaic cycles, terrigenous clastic deposition was about equally balanced with limestone deposition.

Near the end of Canyon (Missouri Series) deposition, apparent rejuvenation in the Ouachita foldbelt and eastern Fort Worth Basin slightly increased paleogradients and significantly increased sediment supply, much of which was second-cycle from earlier Atoka fan-delta facies and easternmost fluvial Strawn facies (fig. 5). With this increased supply of terrigenous clastics, extensive lowermost Cisco (Virgil Series) delta-fluvial systems began building westward across the Eastern Shelf, overlapping Canyon carbonate facies. Thin Cisco delta systems prograded 10 to 15 times across the relatively stable Eastern Shelf of the Midland Basin. Accelerated subsidence of the Midland Basin provided up to 1,500 feet of relief between Cisco shelf edges and the bottom of the Midland Basin (fig. 5). The tectonically stable Eastern Shelf, the large supply of terrigenous sediment, and the great relief between shelf-edge and basin combined to produce extensive, thin fluvial-delta systems which built across the shelf and supplied sediment to thick, basinward-prograding slope-fan facies. During deposition of the uppermost Cisco Group (Wolfcamp Series), sediment supplied from the east again diminished, and thick, low-relief, limestone shelf-edge banks became increasingly prominent.

Following Cisco deposition, extensive carbonate shelf and shelf-edge facies gradually restricted circulation on the landward parts of the Eastern Shelf. Minor deltaic and fluvial systems supplied fine-grained sediment that prograded the coastline

Figure 3. Regional geologic structure map of North-Central Texas. Contoured on top of Home Creek Limestone. After Wermund and Jenkins (1969); published with permission, Dallas Geological Society.

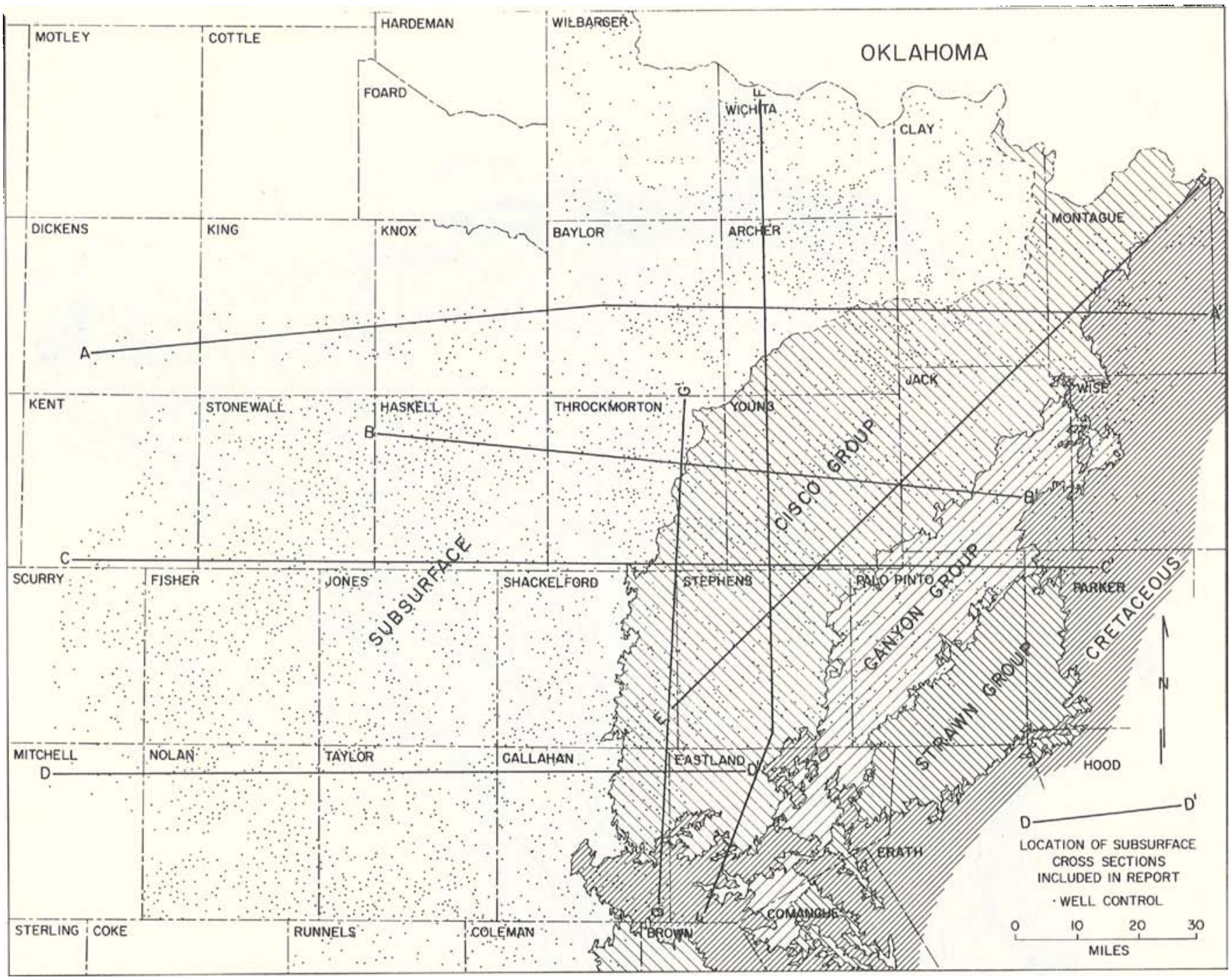


Figure 4. Index to subsurface cross sections showing outcrop of Strawn, Canyon, and Cisco Groups, North-Central Texas. Subsurface control based on approximately 5,000 wells; well data and base maps on open-file, Texas Bureau of Economic Geology.

locally, and that provided sediment to extensive strike-fed tidal-flat systems. These tidal-flat systems accreted basinward and were overlapped by broad supratidal-flat (sabkha) evaporite systems.

Red River Arch-Oklahoma Mountains

The complex history of the Wichita, Arbuckle, and Red River structural elements (Tomlinson and McBee, 1959) is recorded in thick clastic wedges extending southward and southwestward into the northernmost part of North-Central Texas (fig. 1). These arkosic or "granite wash" deposits represent fluvial and fan-delta deposition along steep paleoslopes adjacent to fault blocks near Red River and in southern Oklahoma. The fan-delta systems are associated with contemporaneous limestone deposition on adjacent, structurally positive blocks. Arkosic sediments derived from these source areas contrast with the chert and subgreywacke sandstones derived from an eastern Ouachita foldbelt source (Flawn and others, 1961).

These fan-delta facies do not crop out within the area covered by this field guide, but a typical example of a Canyon Group (Missouri Series) fan delta will be considered in this report in order to demonstrate the nature of sedimentation in the northernmost part of North-Central Texas. The fan deltas prograded basinward as a braided complex; prodelta facies and reworked fan-fringe deposits are of marine origin but the fan plain consists of a cone of shifting braided channels. Fault-controlled sources and high gradients are requisite for perpetuating fan-delta deposition. Fan deltas provide one of the few mechanisms by which graveliferous facies can reach marine environments and by which coarse-grained terrigenous clastics may become closely associated with contemporaneous carbonate facies.

RESOURCES AND DEPOSITIONAL SYSTEMS

Mineral and energy resources in North-Central Texas are closely associated with and can, in fact, be predicted by the depositional fabric of the basin fill. The spatial distribution and the internal facies composition of the depositional systems that fill the basins of the region provide an important tool for understanding and predicting mineral and energy resources. Although most of the resources were found principally by trial and error methods, a post-mortem investigation of a cratonic basin with extensive well control may provide guidelines for future exploration of less mature basins. Also, the knowledge of basin anatomy provides significant information on future environmental problems involving deep-basin disposal of liquid wastes, secondary recovery of oil, subsurface *in situ* mining of coal by liquification, and control of oilfield brines leaking from abandoned wells into surface and ground-water supplies via ancient sandstone conduits.

Oil and gas is concentrated in Strawn and Cisco (fig. 5) meanderbelts and delta-front facies. Cisco slope fans also are important potential reservoirs. Atoka fan-delta facies produce gas in the western Fort Worth Basin. Canyon and Strawn carbonate banks and reefs are important reservoirs, as well as some Cisco shelf-edge carbonates, where dolomitization has provided permeability.

Cisco coals in North-Central Texas (fig. 6) are principally lagoonal; numerous delta-plain coals also occur. Strawn coal is of both embayment and delta-plain origin. The distribution of coals (fig. 6) clearly outlines Pennsylvanian fluvial-deltaic and associated interdeltaic embayments.

Clay for brick, expanded aggregate, and other heavy clay products is principally derived from Strawn and Cisco Group prodelta facies; one Canyon Group prodelta facies is productive. High-kaolin ceramic clay is derived from Cisco (Harpersville Formation) interdeltaic embayment clays that were apparently leached by subaerial weathering and/or by subembayment acidic waters.

Limestone production is restricted principally to Canyon limestone banks or thick open-shelf limestone facies (fig. 5). Copper deposits occur within some uppermost Cisco fluvial channels, but economic deposits are restricted to tidal-flat/sabkha systems in post-Cisco Permian red-bed sequences.

SUMMARY

The fabric of cratonic basin fill is controlled principally by regional and local tectonism and genetically linked depositional systems. As basins evolve structurally, the nature of depositional systems evolves in concert with changing tectonic stability, fluctuating type and volume of sediment, source area tectonics, changing paleogradients, and varying depths of water.

Depositional systems within *foreland basins* evolve principally in response to tectonic cycles in the adjacent geosyncline; fan deltas commonly develop into high-constructive deltas during basin filling as sediment supply and paleogradients diminish. High-destructive, wave-dominated delta systems will develop if high-bedload fluvial systems are introduced to coastlines with an unusually high degree of structural stability; strand plains, barriers, and associated beach and dune facies, or so-called "orthoquartzite" sandstones, typify these systems and tectonic settings.

Rates of subsidence versus sediment supply determine the nature of associated slope systems. Platform and shelf-edge carbonate systems commonly develop on the stable craton until the foreland basin is filled and terrigenous clastics are transported to the craton by fluvial-deltaic systems. Rejuvenation of foreland basin subsidence can repeat the cycle many times.

Depositional systems within *intracratonic basins* reflect the rate of basin subsidence, the relief between marginal shelf or platform areas and the basin, the relative structural stability of shelf versus basin, and the nature of the sedimentary source (e.g., foldbelt or uplifted foreland basin sediments, fault blocks associated with yoked basins, or distant sources in shield or other positive areas). In the absence of a significant terrigenous sediment source, the cratonic basin becomes essentially a carbonate province; if shelf areas are stable and climate is arid, evaporites of the sabkha variety may dominate.

During early subsidence, the cratonic basin may be the site of starved-basin deposition, followed by laterally prograding slope wedges (in deep basin) if a significant sediment supply is available. In this type of terrigenous clastic basin, slope facies become the principal facies that compose the basin fill. If the basin is shallow and relative relief between shelf and basin is slight, slopes will not develop but deltaic systems (assuming proper sediment supply) will fill the basin; prodelta facies then becomes a principal part of the fill.

Local and regional variations can dictate the character of foreland and intracratonic basin fill. Every basin, however, evolves through a series of tectonic stages; each of these stages is reflected in the nature of the depositional system that develops in response to changing basin style. The depositional systems tract preserved in the Pennsylvanian and Permian rocks of North-Central Texas reflects the lateral and vertical transition from foreland basin to cratonic platform, and finally to intracratonic basin with its complex history of accelerating subsidence that dictated a sequence of dominant systems: deltaic, carbonate, slope, and finally tidal-flat sabkha depositional systems.

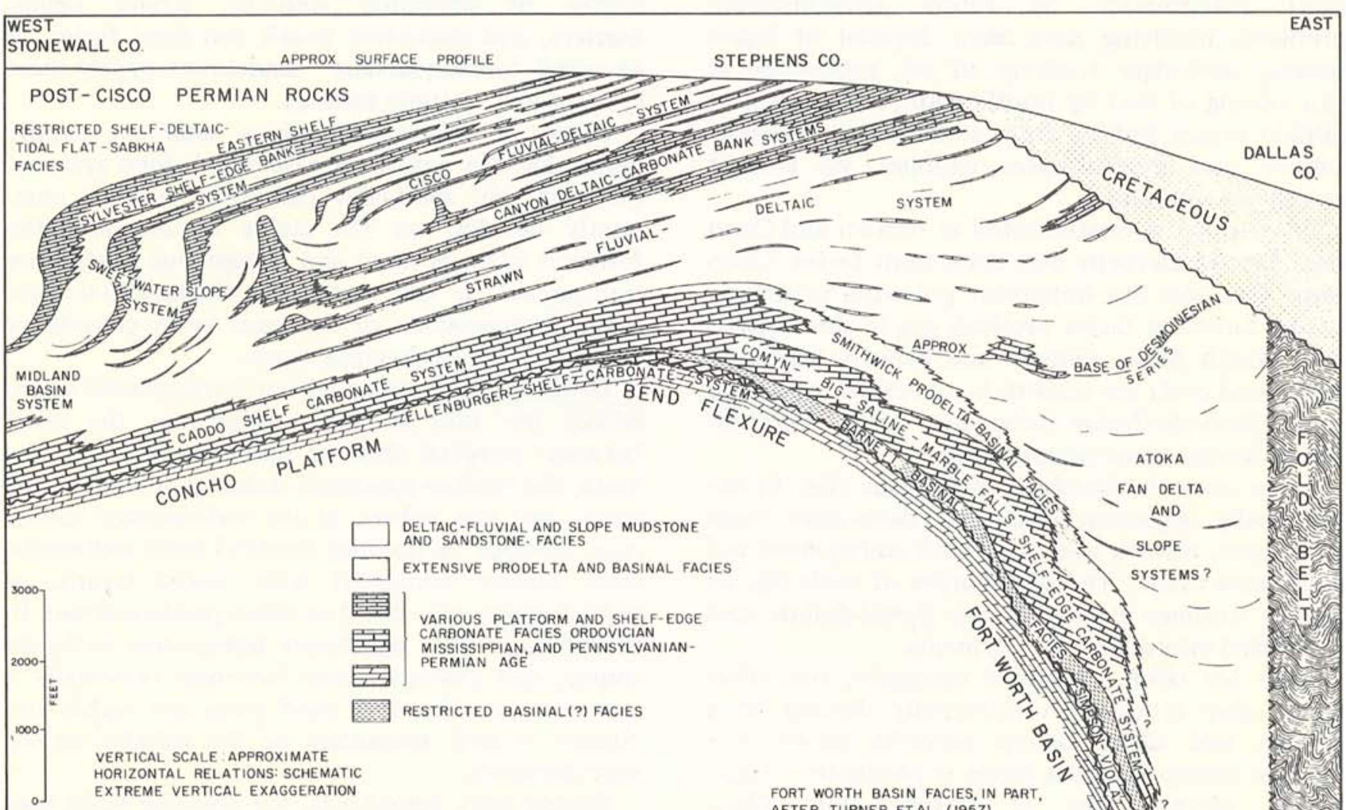


Figure 5. Evolution of depositional systems, North-Central Texas: Fort Worth Basin, Concho Platform, and Eastern Shelf.

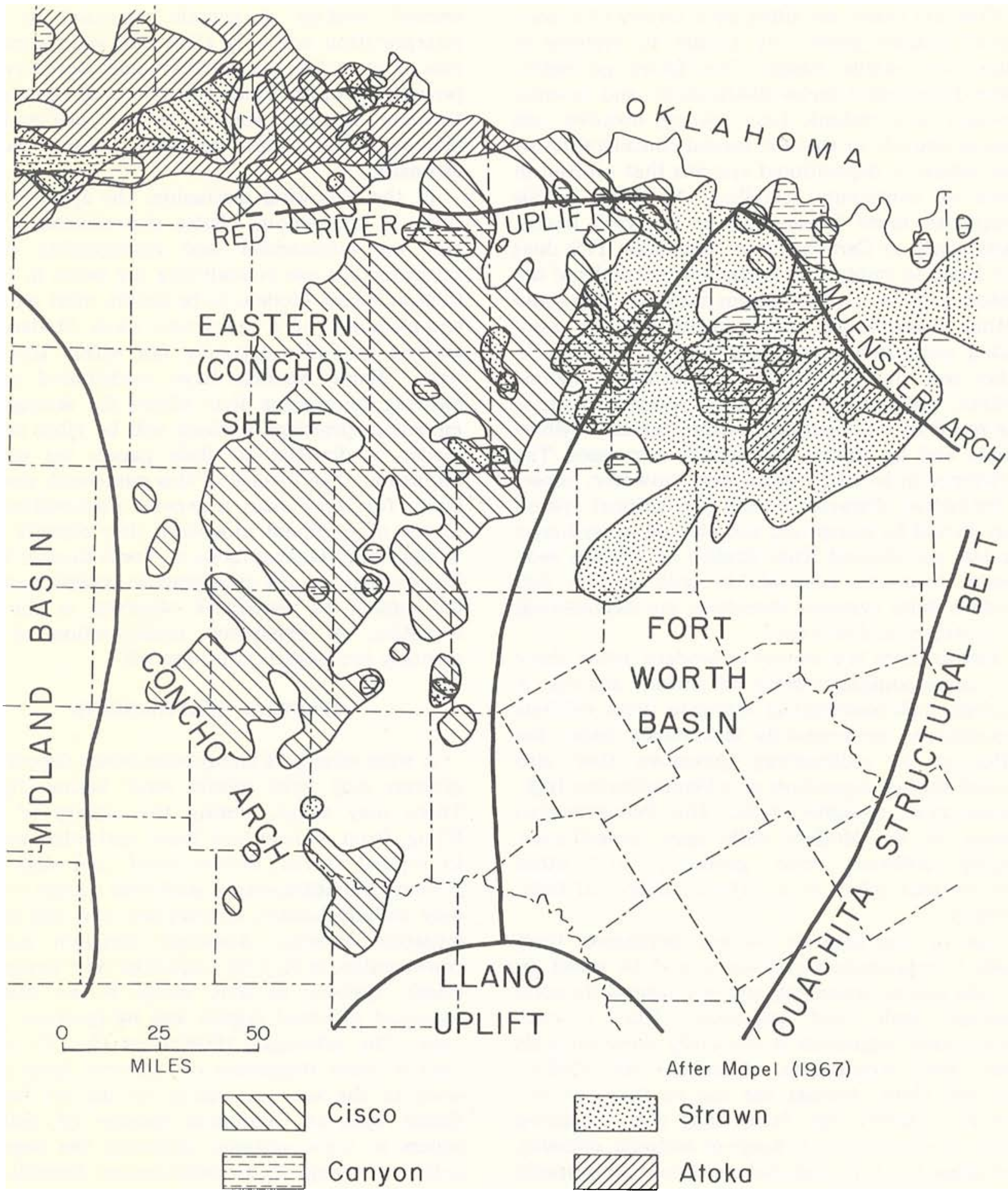


Figure 6. Distribution of Pennsylvanian coal deposits, North-Central Texas. After Mapel (1967).

CRATONIC BASINS: TERRIGENOUS CLASTIC MODELS

L. F. Brown, Jr.

Cratonic basins are filled by a variety of depositional systems genetically similar to systems in other less stable basins. The facies geometry, three-dimensional facies distribution, and internal features in a cratonic basin setting, however, are unique enough to warrant special consideration of the nature of depositional systems that evolved in areas of continental stability. Nowhere is this uniqueness more obvious than in Paleozoic basins, particularly in Carboniferous sequences. This does not mean to imply that Carboniferous rocks of the craton and its confined basins were not deposited within depositional environments and by associated sedimentary processes that were active in other less stable settings. Genetically, a deltaic system, whether in a cratonic or foreland basin, is the result of sedimentation within certain environments and by similar sedimentary processes. The difference in tectonic setting may, however, impart a distinctive character to the depositional system that should be recognized and utilized as predictive models are devised from studies of modern sediments. Common elements in both ancient and modern delta systems, therefore, are depositional environment and process.

Just as there is a variety of Modern deltas, there is a corresponding variety of ancient analogs. A Modern high-constructive elongate delta exhibits depositional environments and builds under the influence of sedimentary processes that also existed during deposition of a Pennsylvanian high-constructive elongate delta. The Pennsylvanian analog of the Modern delta may, nevertheless, display different scale, geometry, and other features that relate to a different degree of basin stability.

Use of stratigraphic models developed from Modern depositional systems should be based on process and environment, and not necessarily upon absolute scale and geometry. The process-environment approach is obviously more difficult than direct comparison of ancient and Modern systems. Only through the use of these genetic factors, however, can facies that were deposited under an almost infinite range of tectonic, climatic, and other local and regional conditions be properly interpreted. Realizing that Modern depositional systems present a wide spectrum of variations, one can only hope that, through study of facies in terms of process and environment, a valid interpretation can be made for the enormous variety of ancient analogs. A genetic approach to facies interpretation not only allows for valid identification of ancient depositional systems, but provides a powerful tool by which the effects of variations in tectonic setting, source areas, paleogradients, climate, and other geologic factors can be estimated.

In the following discussion, the spectral variations in terrigenous clastic depositional systems will be summarized and stratigraphic criteria presented for use in analyzing the facies in North-Central Texas. Models, to be useful, must represent end-members of a spectrum; most Modern and ancient examples naturally fall within this spectrum. Many workers have contributed to the growing knowledge that allows for stratigraphic modeling; principal workers will be cited and the reader is directed to their papers for detailed discussion. The format of this guidebook does not allow for more than a general presentation and review of pertinent models as they directly relate to the Pennsylvanian facies of North-Central Texas. Emphasis is on the stratigraphic criteria that may be applied to sequences observed at the field localities; an exhaustive consideration of sedimentary processes is not intended.

SPECTRAL RELATIONSHIPS

A wide variety of terrigenous clastic depositional systems may exist within most basins (fig. 7). These may range, during the history of basin filling, from on-land fans, lakes, and eolian systems to dip-fed fluvial, deltaic, shelf, and slope-basin systems. Complementary strike-fed marine systems may include barrier, strand-plain, and bay-lagoon-estuarine systems. Although variation may be considerable, it may be helpful to view terrigenous clastic systems as they relate to an idealized *sediment dispersal system* and its resultant *facies tract*. The schematic illustration (fig. 7) can be used to show dispersion of sediment from inland areas to the sea, principally via dip-fed fan and fluvial systems; minimum storage of sediment occurs in these systems. Although the degree of sediment storage in the delta system depends upon factors such as rate of basin subsidence (stability), the further dispersion of sediment may continue in two ways: (1) dip-feeding across the shelf, via delta progradation or tidal transport, to supply the slope and basin; and/or (2) strike-feeding along the basin

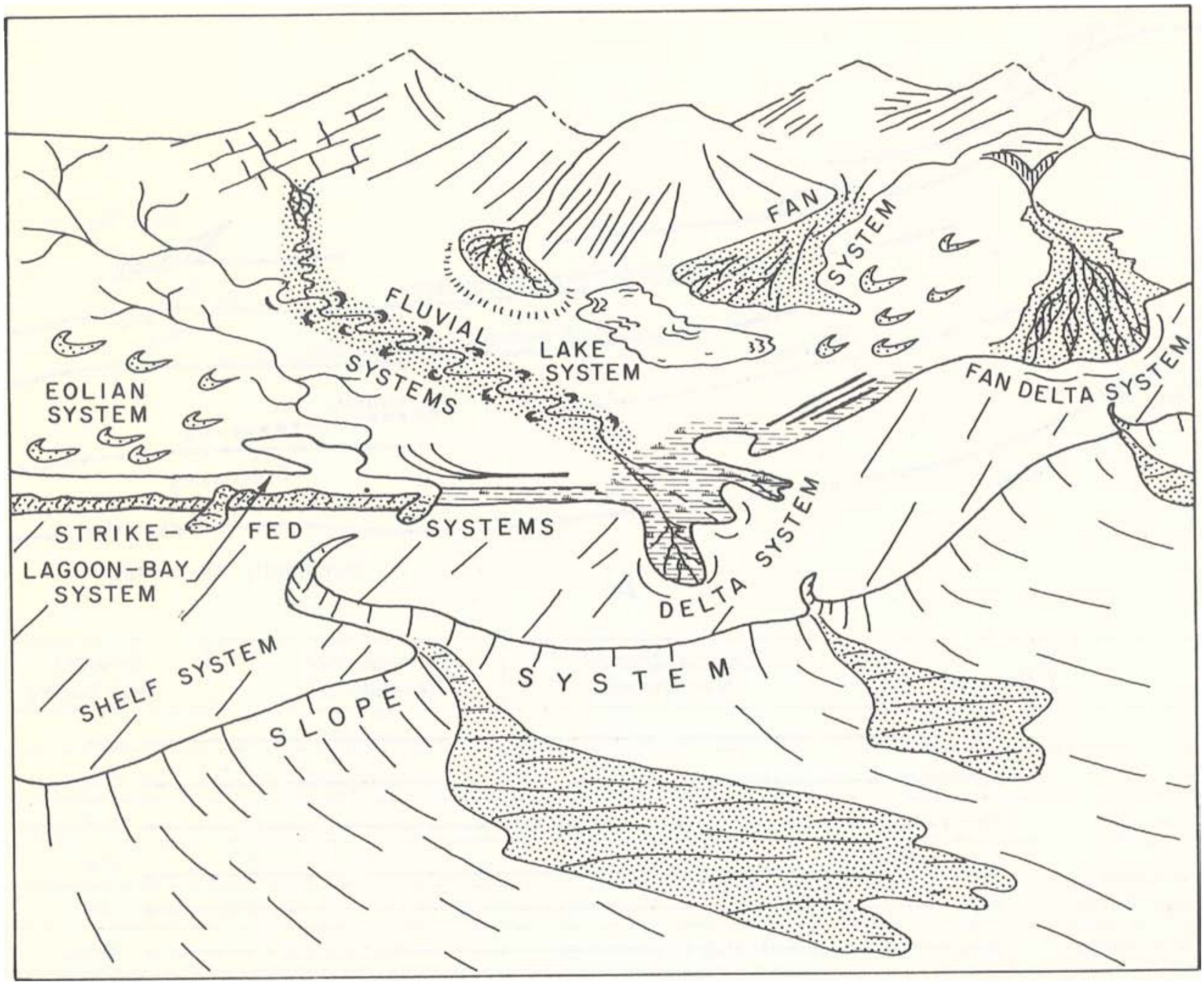


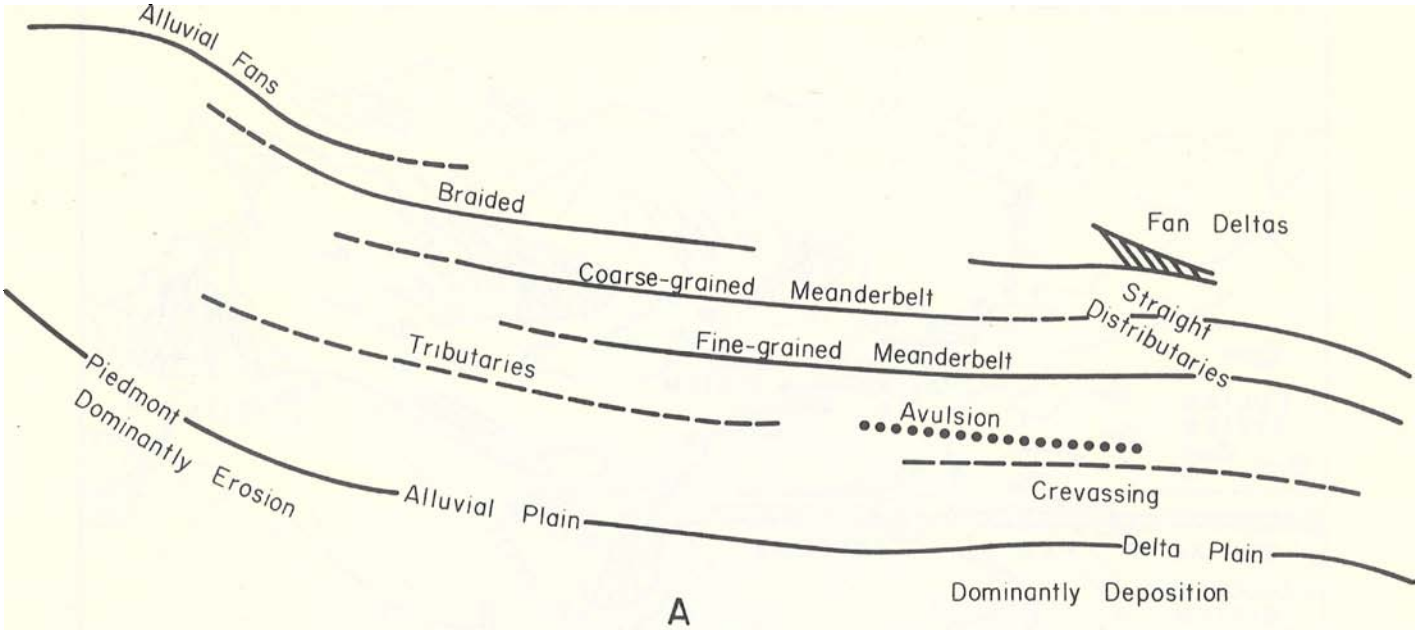
Figure 7. Schematic perspective of terrigenous clastic depositional systems. (Original by A. J. Scott.)

margin to supply barriers, strand plains, and, through tidal inlets, bay-lagoon-estuary systems.

Fluvial and deltaic facies along this idealized dispersal system are well exposed around the margins of most cratonic basins such as the North-Central Texas area. Some strike-fed facies will be observed. Slope-basin dispersion of sediment will be briefly considered but these facies are deeply buried in most cratonic basins. Much of the following discussion of terrigenous clastic models comes from the synthesis by Fisher and Brown (1972) and Fisher and others (1969), and is based on the work of many authors.

FLUVIAL SYSTEMS

An important segment of a sediment-dispersal system is the stream; a series of dip-oriented views of river (and facies) types (fig. 8A) exhibits a range of depositional variations: braided, coarse-grained meanderbelts, fine-grained meanderbelts, and distributaries associated with deltas. Such a progression of fluvial systems is obviously idealized, but it allows for a general perspective of some of the factors that either determine the type of fluvial system or that result from deposition within the particular fluvial system. Such factors include gradient, channel flow, discharge rate, character of sediment load, geometry of resulting sand bodies, and the nature of levees (fig. 8B). The geometry of the resulting fluvial sandstone deposit is very important in the analysis of ancient basins. Figure 9 demonstrates the relationships between discharge and an idealized fluvial system composed of the various spectral types of river-deposited facies. The following sections describing the spectral fluvial types are extensively illustrated with diagrammatic sketches. Many workers have discussed various



	Braided	Coarse-grained Meanderbelt	Fine-grained Meanderbelt	Straight Distributary
Gradient	High →	→	→	Low
Channel flow	Unconfined →	→	→	Confined
Discharge rate	Flashy →	→	→	Continuous
Bedload / suspended load	High →	→	→	Low
Sand/mud (deposit)	High →	→	→	Low
Sand body (deposit)	Wide →	Multilateral →	Multistoried →	Narrow
Levees	Slight →	→	→	Prominent

B

Figure 8. Spectrum of features along idealized fluvial systems. A. Idealized fluvial facies tract. B. Spectrum of features in fluvial systems.

aspects of fluvial environments, processes, and resulting facies. The reader is directed to a comprehensive discussion of alluvial sediments by J.R.L. Allen (1965) for a broad perspective and for sources of data about fluvial systems. A summary of terrigenous clastic facies, including references, by LeBlanc (1972) provides an excellent introduction to fluvial sedimentation.

Braided Systems

Recent studies by Ore (1963, 1965) and Smith (1970) have provided significant insight into the deposition and internal nature of braided streams. Braided streams (fig. 10A) are best developed in upstream areas (figs. 8, 9) with high gradients, low but flashy discharge, and high sediment bed load. Braiding may also occur at lower gradients where streams cross sandy outcrop belts and are locally choked with coarse-grained bed load. Channel-fill units are flat bedded, discontinuous, lenticular to tabular. Sedimentation is principally along 1) longitudinal bars (fig. 10B) that are up to several hundred feet long, tens of feet wide, and 2 or 3 feet thick and that parallel stream flow, and 2) along migrating transverse bars or sand waves that are 2 or 3 feet high and up to tens of feet wide, and that are oriented normal to stream flow. Sedimentary structures are commonly horizontal bedding and tabular foreset cross-beds; ripple

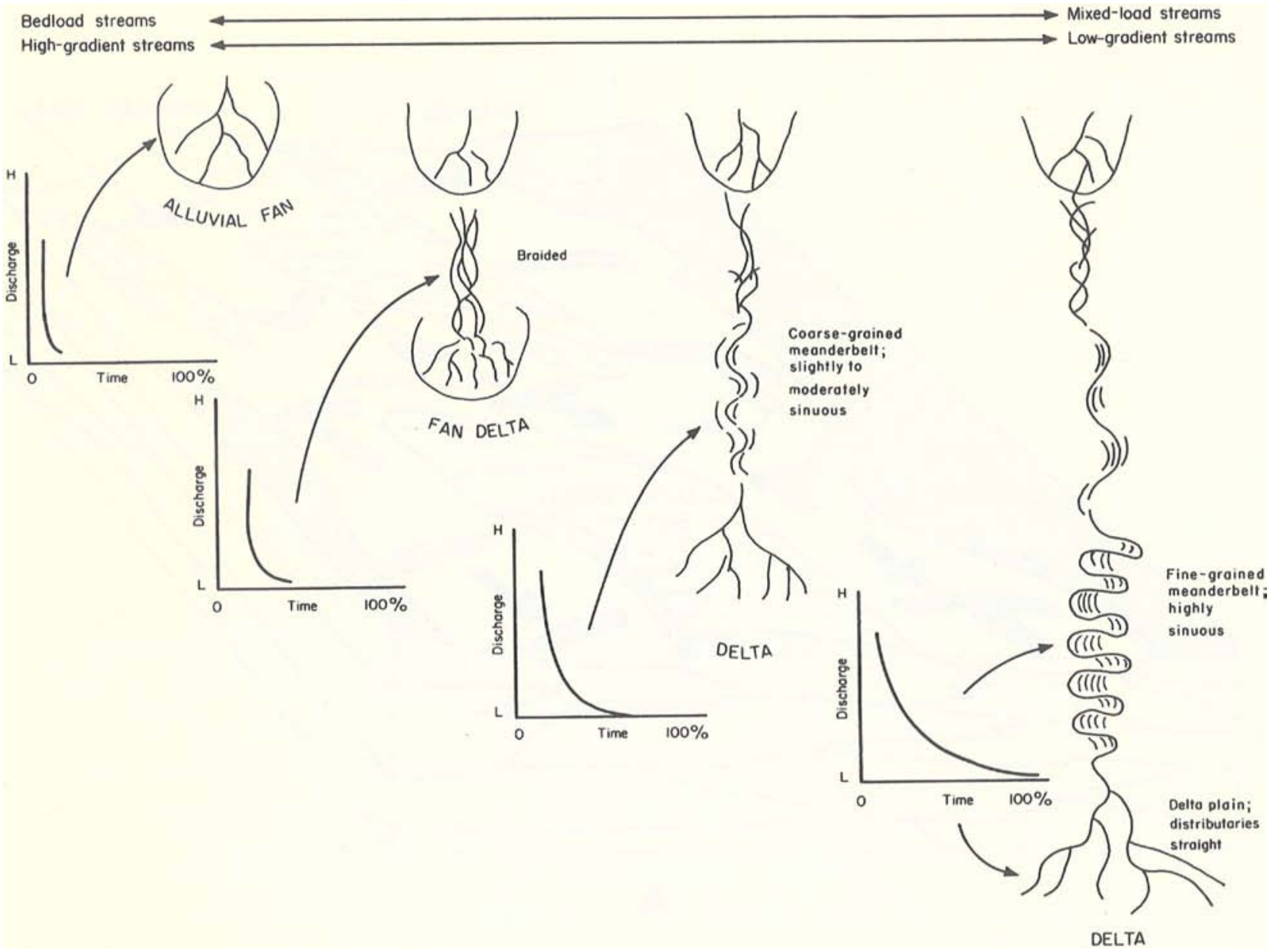


Figure 9. Fluvial systems and associated discharge characteristics.

cross-laminations are rare. Sediments in braided streams are generally coarse grained, commonly medium- to coarse-grained sand and gravel-sized material; muds or silts are rarely preserved within these systems. Channel scour is slight and is normally restricted to washouts in front of transverse bars and to the flanks or upstream ends of longitudinal bars; bars may be dissected during subsequent periods of discharge.

Braided sand bodies are multilateral with high width/thickness ratios (fig. 10). They are deposited within low-sinuosity streams with anastomosing channels. Flow-directional features (cross-beds) may vary considerably in unconfined flow. Braided systems deposit very little overbank mud; levees are absent or poorly developed. Little organic material is preserved in braided systems.

Distinguishing features of braided systems include 1) few stratification types; 2) poor lateral continuity of depositional units that may be characterized by parallel beds, tabular cross-beds, and/or trough cross-beds; 3) rare ripple cross-laminations; 4) high sand content; and 5) sand-body geometry that is multilateral. Idealized vertical sequences within braided systems (fig. 15A) display no definite vertical variations in grain size or in sedimentary structure; the sequence is typically composed of mixed trough cross-beds, tabular cross-beds, and horizontal beds with sand and gravel distributed throughout. The basal and upper contacts with other facies are commonly abrupt; top strata or overbank-levee deposits are rare.

Coarse-Grained Meanderbelt Systems

Coarse-grained meanderbelt systems (fig. 11) were described and interpreted by McGowen and Garner (1970). These systems occupy a position about midway in the spectrum of fluvial types between braided and fine-grained meanderbelts (figs. 8, 9). They are in the lower range of moderate- to high-bed-load dispersal systems controlled by moderate gradients and/or moderate sandy bed-load source areas. Braiding might occur

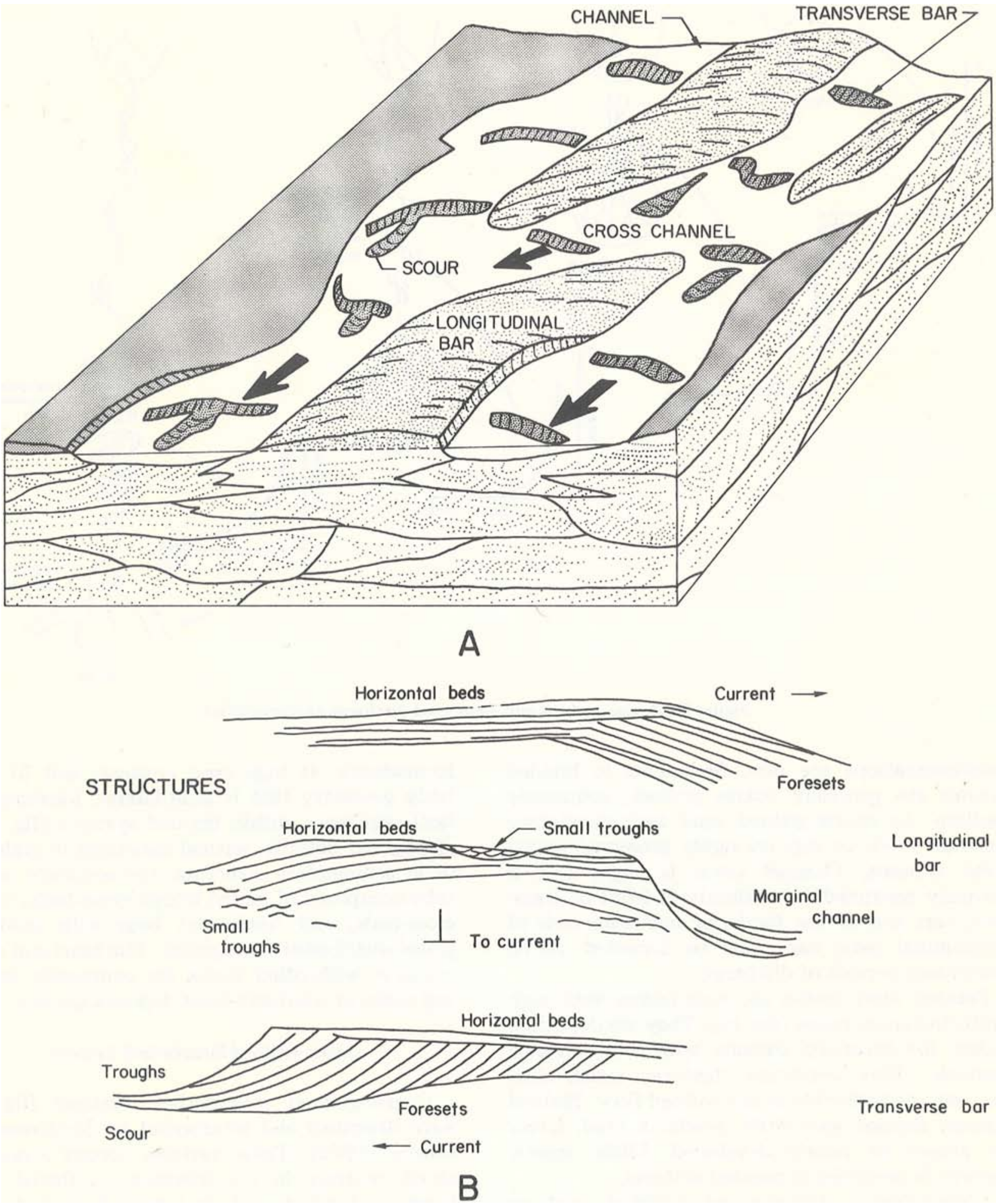


Figure 10. Depositional model of an idealized braided fluvial system. A. Block diagram showing bedforms, sedimentary structures, and multilateral-sand geometry. B. Sedimentary structures deposited by longitudinal and transverse bars. Modified from Ore (1963, 1965) and Smith (1970); described by Fisher and Brown (1972).

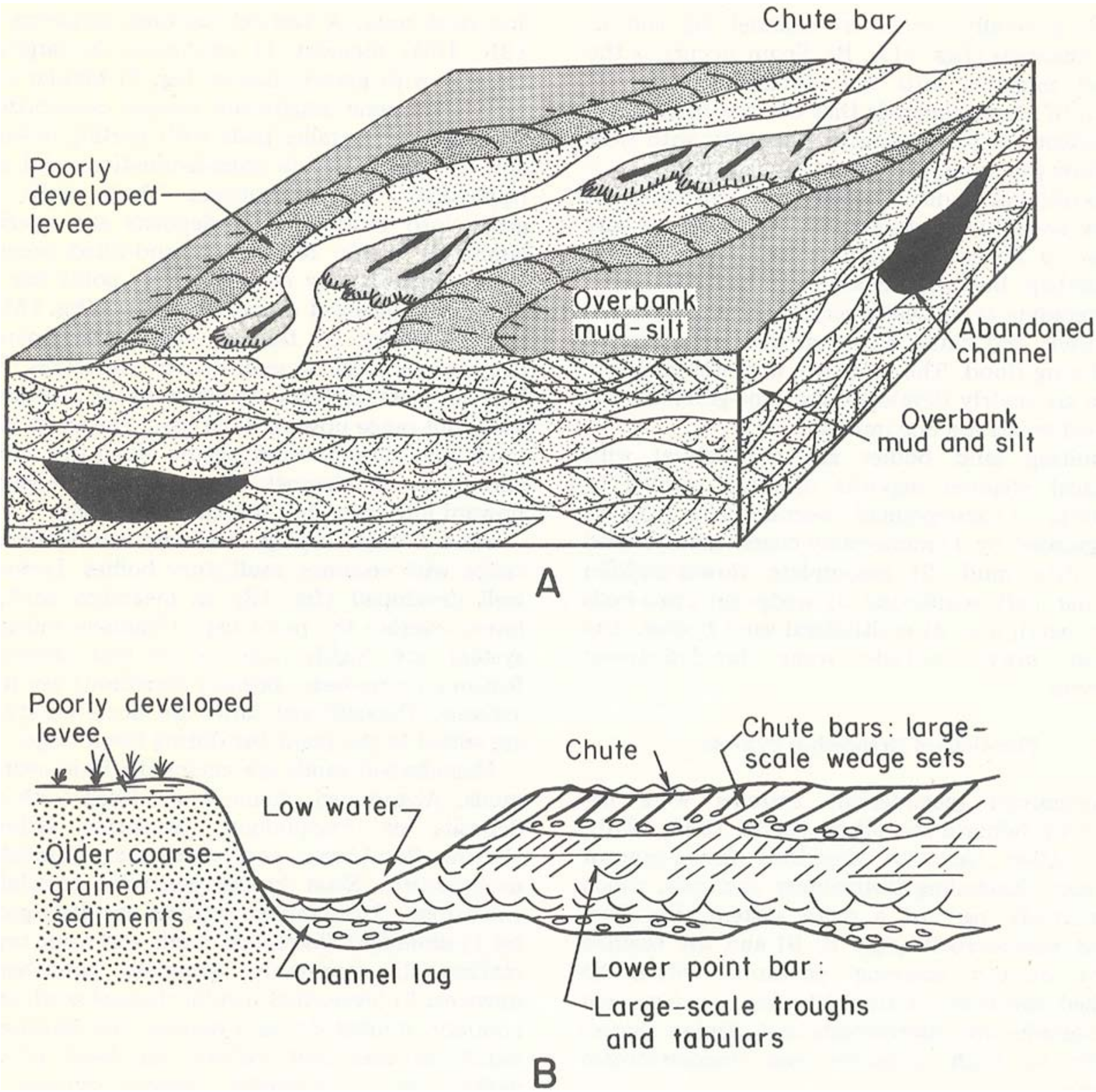


Figure 11. Depositional model of an idealized coarse-grained-meanderbelt fluvial system. A. Block diagram showing bedforms, sedimentary structures, and multilateral-sand geometry. B. Schematic cross section of coarse-grained point-bar deposits. After McGowen and Garner (1970).

in the system if the banks were not stabilized by vegetation. Sand units deposited within these systems are multilateral, composed of partly developed point bars and channel-fill (fig. 11A). Sand bodies have high width/thickness ratios. Sedimentary structures include moderate- to large-scale trough cross-beds and wedge sets, and some tabular cross-beds and small-scale trough cross-beds. Very few horizontal or ripple cross-laminations occur in the system. A vertical sequence (upward) of structures (fig. 15C) may include 1) large-scale troughs with channel lag; 2) moderate-scale trough and tabular cross-beds; 3) wedge sets or avalanche foreset beds (chute bars); and 4) small-scale trough or tabular cross-beds. No regular vertical change in grain size has been recognized, although the lower preserved point-bar sequence displays an abbreviated fining-upward sequence.

Coarse-grained meanderbelts are composed of coarse-grained sand to gravel; very little mud or silt occurs within the system. Coarsest sediment (gravel) generally occurs as channel lag and in chute channels (figs. 11A, B). Scour occurs as the channel migrates into the cutbank and at the bottom of chute channels that cut the basal point bar. Streams display moderate sinuosity with flow indicators (cross-beds) moderately constant.

Depositional units within the meanderbelt include laterally accreting coarse-grained point bars (similar to lower and middle bar in fine-grained meanderbelt but with coarser grained sediment), and aggrading or vertically accreting chute channel-lag gravels and chute bars that develop on point bars during flood. The sequence migrates laterally. Levees are poorly developed and fine-grained overbank sediments are uncommon.

Resulting sand bodies are multilateral with individual channel deposits oriented parallel to paleoslope. Coarse-grained meanderbelts may be distinguished by 1) moderately coarse-grained sand with little mud; 2) incomplete (lower-middle) point-bar part sequences; 3) wedge-set cross-beds (chute bars); and 4) multilateral sand bodies. The system may include some braided-stream structures.

Fine-Grained Meanderbelt Systems

Fine-grained meanderbelt systems were described by Bernard and others (1962, 1963, 1970); J.R.L. Allen has also described fining-upward sequences. Excluding distributary channels, which are uniquely part of a delta system, the fine-grained meanderbelt (figs. 8, 9) and the braided system occupy extreme positions within an idealized spectrum of fluvial types; coarse-grained meanderbelts are intermediate and display characteristics of both point-bar and braided-stream deposits.

Fine-grained meanderbelts (fig. 12) develop under low gradients, moderately high and relatively uniform discharge, and a high suspended load. Channel-fill units are multistoried and asymmetric in cross section. Erosion occurs at the base and cutbank; channel deposits are transitional at the top with overbank and levee deposits. Sand bodies composed of superposed channel-point-bar units are narrow and elongate parallel to paleoslope.

Sedimentary structures include moderate- to large-scale trough cross-beds, a few tabular cross-beds, some small-scale trough and tabular cross-beds, and a variety of ripple cross-laminations. Levee deposits are extensively root-mottled with concretions; overbank muds are laminated to mottled with some delicate ripple cross-laminations and root casts. A vertical (upward) sequence (fig. 12B, 15D) includes 1) moderate- to large-scale troughs with gravel channel lag; 2) tabular cross-beds and some small-scale trough cross-beds; 3) horizontal or parallel beds with parting lineation; and 4) current ripple cross-laminations and some ripple-drift cross-laminations. These units may grade into mottled levee deposits and overbank laminated muds. Mud- and sand-filled erosional swale deposits may cut the upper point bar. The complete, idealized sequence displays (fig. 15D) an upward fining of texture and a corresponding decrease in scale of sedimentary structures. Point bars in these systems are generally of fine-grained sand, but range upward from basal gravels to topset muds and silts. Erosion occurs along the cutbank and base of channel; deposits are transitional upward into levee and floodplain deposits.

Sand bodies display moderate width/thickness ratios with common multistory bodies. Levees are well developed (fig. 12); as meanders shift, the levees overlap the point bars. Channels within the system are highly sinuous so that directional features (cross-beds, primary lineation) are highly variable. Depositional units are accretionary and are added to the point bar during flood stage.

Meanderbelt sands are enclosed within overbank muds. Abandoned channels are filled with splay deposits or fine-grained, plant-rich sediment. Narrow flood-basin coal units may parallel the meanderbelt. Sand bodies generally parallel the paleoslope. Fine-grained systems are distinguished by 1) abundant floodplain muds and some organic matter; 2) commonly complete point-bar sequences; 3) levees that overlie channel sand; and 4) common multistory sand bodies. The thickness of individual sand units reflects the depth of water within the meandering channel during peak discharge.

Distributary-Channel Deposits

Various workers, principally Fisk (1955, 1961) and Frazier (1967), have supplied information on the internal nature and external geometry of straight, stabilized distributary channels (fig. 13). These channels (figs. 8, 9) are components of high-constructive delta systems (Fisher and others, 1969). They are built by streams with high, relatively uniform discharge with sufficiently high mud content for levee construction and gradual channel subsidence. Gradients are very low on delta plains. Sand deposits within the channel display vertical aggradation as levee stability pre-

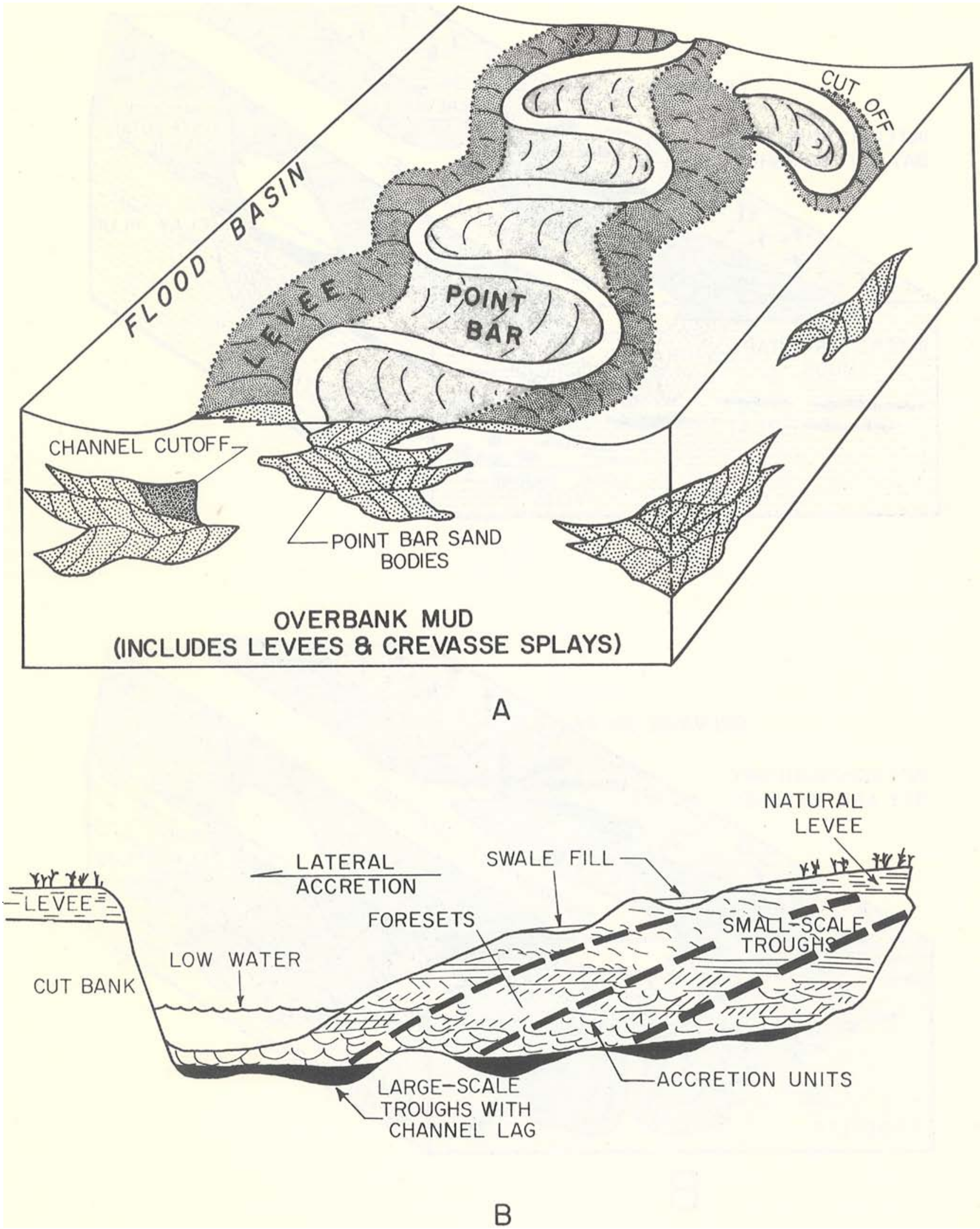


Figure 12. Depositional model of an idealized fine-grained-meanderbelt fluvial system. A. Block diagram showing bedforms, sedimentary structures, and multistory geometry. B. Schematic cross section of fine-grained point-bar deposits. After Bernard and others (1963); described by Fisher and Brown (1972).

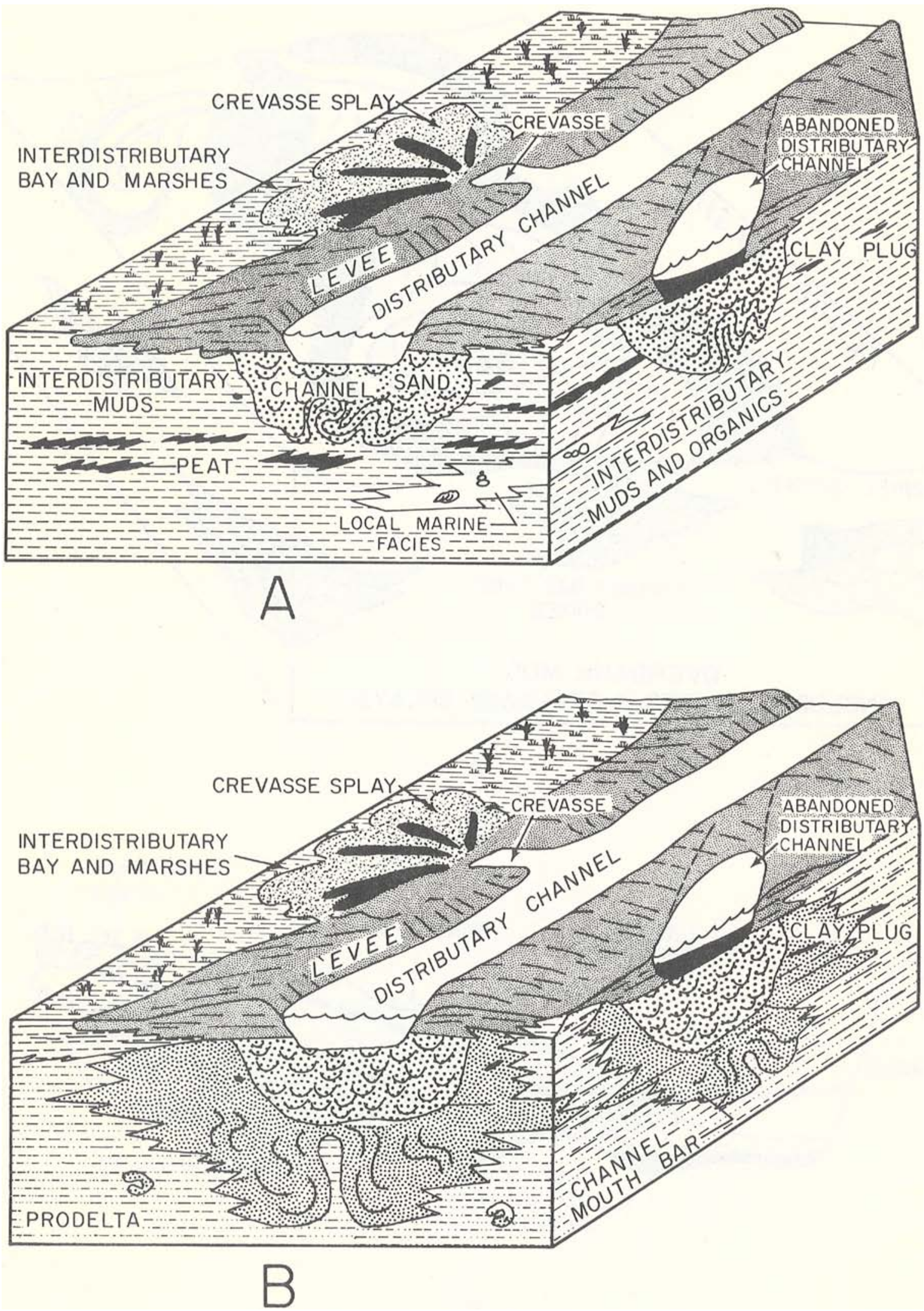


Figure 13. Depositional model of idealized distributary-channel-fill and associated deposits. A. High-constructive lobate delta-plain setting displaying extensive aggradation. B. High-constructive elongate-delta setting displaying extensive progradation. Adapted from Fisk (1955, 1961), Frazier (1967); described by Fisher and Brown (1972).

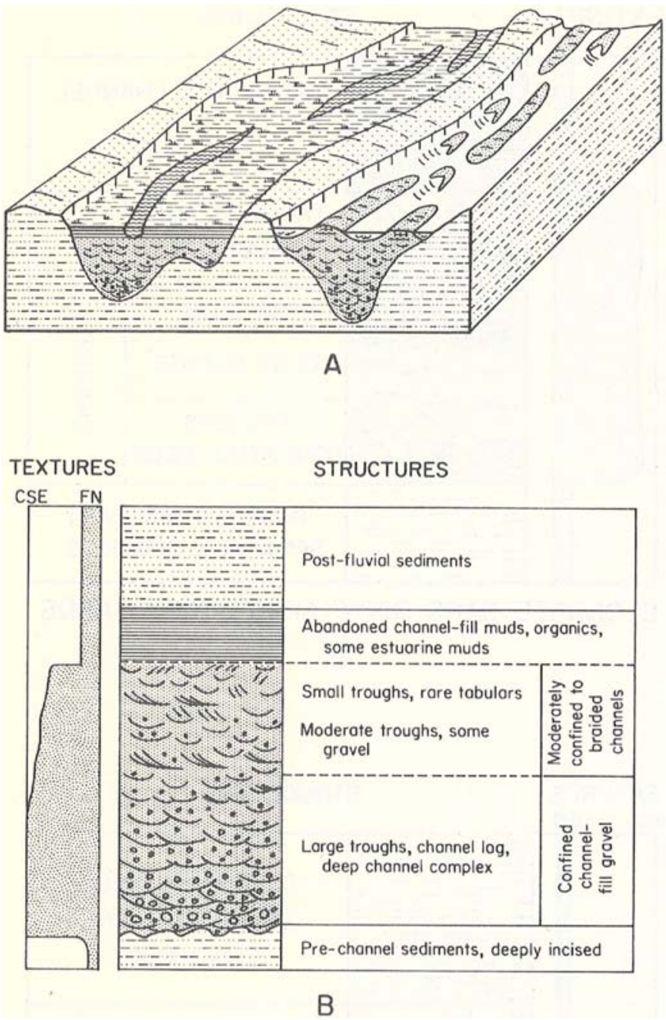


Figure 14. Depositional model of an idealized valley-fill fluvial system. A. Block diagram showing nature of aggradational-fill deposits. B. Idealized vertical sequence. In part after Shelton (1972).

cludes significant lateral accretion. Channels, and, therefore, channel-fill deposits, are symmetrical in cross section with the base convex downward and the top relatively flat. The sandstones may display extremely low width/thickness ratios because of extreme multistorying of channel fill. Sedimentary structures are dominantly trough cross-beds with some ripple-drift cross-laminations near channel margins; compactional deformation commonly destroys many of the internal, primary sedimentary features. An idealized vertical sequence (upward) within a distributary channel-fill deposit (fig. 15B) commonly exhibits 1) massive, sometimes highly deformed sands with some small-scale injections and convolutions; 2) moderate-scale trough cross-beds; 3) some trough and tabular cross-beds; 4) ripple-drift cross-laminations migrating away from the thalweg and transitional with levee deposits; and 5) laminated abandoned channel-fill muds and organic matter that are commonly burrowed. Channel-fill muds are commonly scoured during subsequent reoccupation of channels. No significant vertical trend in scale of sedimentary structures occurs in the channel fill.

Two settings for distributary channels are possible (fig. 13A, B). The channel may be cut into delta-plain facies (fig. 13A). In this case avulsion shifts the channel across an interdistributary bay to a new site of progradation, typical of Holocene-Mississippi lobate deltas. When the channel is part of a significantly prograding lobe, it will build over and cut into its own channel-mouth bar and delta front (fig. 13B); this is typical of the Modern Mississippi elongate or birdfoot delta.

Channel fill is fine- to medium-grained, poorly to moderately sorted sand. Mud-chip conglomerates and wood fragments are also common. No vertical fining in texture has been noted. Scour within the channel is slight as subsidence of the channel results in extensive vertical accretion or aggradation; the base of a channel is generally contortional rather than erosional (fig. 13). Multistory channel-fill sands define thick, elongate bodies that generally parallel paleoslope; bodies are regionally distributive in pattern. Levees are well developed but normally flank rather than overlie the channel fill. Directional features (cross-beds) are very uniform in the confined channel deposits of the relatively low sinuosity stream. Units consist of bed-load sediments deposited within low- to transitional-flow regime during dropping flood level; levee deposits, crevasse splays, and interdistributary muds are built during peak discharge. Organic matter is common within the adjacent bay; fossils also occur if conditions are sufficiently marine.

Distinguishing features include 1) elongate, symmetrical sand bodies enclosed in muds and organic deposits; 2) distributive patterns; 3) uniformity in vertical textures and structures; 4) sand fill flanked by levee deposits; 5) multistory channel-fill deposits; and 6) basal beds that are commonly contorted.

Confined Valley-Fill Deposits

These deposits fill small valleys eroded into underlying sediments (fig. 14A). They originate on alluvial plains (fig. 8) as a result of a base-level change induced by one or more factors such as 1) minor eustatic or relative (subsidence) change in

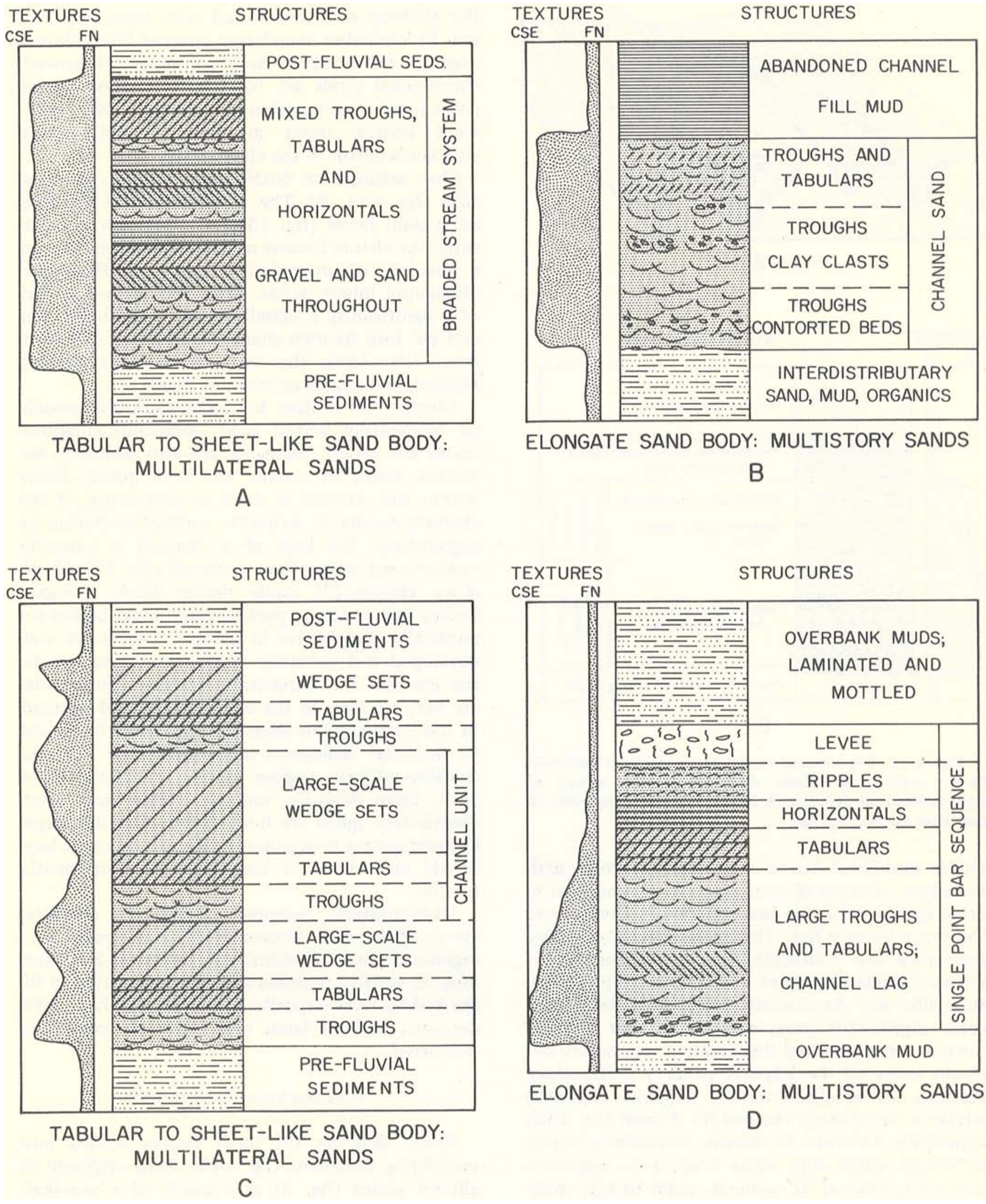


Figure 15. Idealized vertical sequences, fluvial depositional systems. A. Braided stream deposit. B. Distributary-channel-fill deposit. C. Coarse-grained-meanderbelt deposit. D. Fine-grained-meanderbelt deposit. In part based on Ore (1963, 1965), Smith (1970), McGowen and Garner (1970), and Bernard and others (1963); described by Fisher and Brown (1972).

sea level; 2) differential tectonic subsidence and/or elevation of source area; and/or 3) major avulsion in overextended fluvial-deltaic system followed by readjustment in response to the steeper gradient. Channel erosion related to avulsion would continue until upslope erosion of the channel, coupled with continued progradation of its delta across the stable shelf, combined to flatten the profile and initiate aggradation of valley-fill deposits.

Deposits fill superimposed valleys that may be deep and steep-sided or broad and shallow. These channels or small valleys may be straight to sinuous. Basal channel fill is normally very coarse gravel-filled troughs. Confined flow moves graveliferous transverse bars several feet high. Gravel content decreases upward (fig. 14B), coincident with decreasing scale of trough cross-beds; scale of troughs diminishes abruptly when the channel aggrades to a level where a significant decrease in flow confinement occurs. In upper parts of the valley fill under diminished confined flow, medium- to small-scale trough cross-beds dominate, with some tabular bodies and horizontal bedding indicating braiding of channels (fig. 14A). There is a very poorly developed upward fining of sediment size and scale of trough cross-beds. Scour occurs throughout the deposit as troughs wash out and are filled by migrating transverse bars. Channels are relatively straight, especially in the basal fill; flow indicators may be as uniform as those within distributary channels. The entire valley fill, excluding abandoned channel fill, is composed of gravel and medium to coarse sand; wood and eroded blocks of bank material occur within the deposits.

Some channels are completely filled, and unconfined braided facies spread laterally beyond the limits of the buried valley. Other channels or valleys are abandoned before final filling; these partially filled channels contain fissile mud and organic material, or, if near to the shoreline, estuarine facies may encroach upon the channel as compaction continues.

Distinguishing features include 1) graveliferous, coarse-grained composition; 2) dominance of large- to moderate-scale trough cross-beds; 3) slight upward fining in grain size and upward decrease in scale of troughs; 4) muddy organic sediment on top of coarse sand and gravel as a result of abrupt abandonment; and 5) base of channel in contact with a variety of subjacent facies including marine limestones.

DELTA SYSTEMS

Many workers have contributed to an understanding of deltaic environments, processes, and facies. Several recent summaries provide the reader with a broad background on the subject: LeBlanc (1972); Morgan (1970a, b); Fisher (1969); Fisher and others (1969); and Fisher and Brown (1972).

Deltaic deposition involves the discharge of water and transported sediment (bed load and suspended load) by a river into a standing body of water. The interaction of river and marine processes determine to a considerable extent the nature of the resulting delta system. Critical variables include 1) the nature of sediment input (size, rate); 2) relative water densities of river and water body; 3) waves, currents, tides within the water body; 4) depth of water into which delta is building; 5) nature of the substrate of the water body; and 6) the structural style of the depositional basin (cratonic, unstable). Scruton (1960) and Coleman and Gagliano (1964) showed that delta deposition is cyclic: a constructive phase occurs when river processes dominate to prograde the river mouth basinward; and a destructive phase occurs when marine processes dominate to rework and modify the delta. Construction and destruction may be temporally distinct with constructional processes dominant; these deltas have been called high-constructive deltas (Fisher, 1969). When constructive and destructive processes are essentially contemporaneous, with destructional processes dominant, the deltas have been called high-destructive (Fisher, 1969). Fisher established four delta types which, like the spectrum of fluvial models, provide some insight into deltaic systems, their processes, environments and resulting facies. Fisher further defined high-constructive (river-dominated) deltas on the basis of sand geometry: high-constructive elongate and high-constructive lobate. He classified high-destructive (marine-dominated) deltas on the basis of the dominant marine process: high-destructive, wave-dominated; and high-destructive, tide-dominated (Fisher, 1969; Fisher and others, 1969).

High-constructive deltas exhibit extensive, fluvially dominated environments, processes and facies; high-destructive deltas are dominated by marine environments and processes. The modern Mississippi is a high-constructive delta; the birdfoot lobe is an active elongate type and the abandoned Lafourche, Teche, and St. Bernard lobes are lobate types. High-destructive, wave-dominated deltas include most modern deltas such as the Rhone, Po, and Nile. High-destructive, tide-dominated deltas are those such as the Mekong, Papua, and Irrawaddy. The reader is referred to previously cited reports dealing with specific aspects of deltaic systems.

Within the spectrum of delta types, only high-constructive deltas have been recognized to date in the Pennsylvanian of North-Central Texas. These deltas, high-constructive elongate (bar-finger type) and high-constructive lobate systems, have been inferred using facies, environment, and process information from the Modern Mississippi system (fig. 16). As in all such classifications, some deltas of North-Central Texas may fall between the elongate and lobate end members of the spectrum.

High-Constructive Systems

High-constructive systems are river-dominated deltas formed by progradation under low bed load/suspended load ratios. Progradational facies (prodelta, delta-front, channel-mouth-bar facies) and aggradational facies (distributary-channel, levee, crevasse-splay, coal, interdistributary-bay facies) constitute the bulk of the system. Contemporaneous destructional processes are minor and destruction is a temporally distinct phase following delta abandonment; marine destructional facies are relatively minor in such systems.

Progradational sand facies are built basinward over relatively thick prodelta muds; after abandonment, the delta subsides, allowing thin destructive facies (and eventually shelf facies) to transgress the foundering delta platform.

Source areas are normally distant, and fluvial systems at the head of the delta are meanderbelts. Sediment input is relatively high and uniform in Modern examples. These deltas exhibit pronounced constructional-destructional phases. Constructional facies are well developed and include both progradational and aggradational facies. Destructional facies are commonly restricted to distal parts of the system and consist of small barriers, marsh, and reworked strand-plain sands. High-constructive systems commonly have associated strike-fed systems such as barriers, strand plains, and bays. Sand/mud ratio is low; this is a factor in differential compaction and soft-sediment deformation that are common in high-constructive systems.

A delta sequence in North-Central Texas includes a superposed stack of coarsening-upward facies, all of which are intergradational except for erosion at the base of distributary and crevasse channels. Vertically (upward) this sequence is composed of the following: 1) *prodelta* mudstones, laminated, plant-rich, intercalated siltstones, relatively unfossiliferous, proximal (top) section with flow rolls and other deformed sandstones; 2) *delta-front* sandstones, fine- to medium-grained, thin-bedded in lobate deltas (with horizontal laminations, ripple cross-laminations, wave ripples, growth faults), massive in elongate deltas (highly deformed, load structures at base); 3) *channel-mouth-bar* sandstones, moderately to well sorted, fine- to medium-grained laminae, trough cross-beds, structures commonly deformed or destroyed by intrusion and compaction, bar crest scoured by distal distributaries; 4) *distributary-channel fill*, trough cross-beds, medium- to coarse-grained, clay chips, wood fragments, commonly deformed; 5) *delta-plain facies*, crevasse-splay sandstones with channel-fill ripple cross-laminations, interdistributary-bay mottled mudstones locally containing fossils and coal, mottled flood-basin mudstones; 6) *destructional facies*, commonly bars, locally calcareous, ripple-drift cross-laminations, and small-scale trough cross-beds, burrows; and 7) *transgressive facies*, marine limestones and bioturbated relict deltaic mudstones.

The geometry of high-constructive sand facies is greatly dependent upon the relative thickness and depositional rate of prodelta mud facies, which control the volume of sand storage. The tectonic stability of the structural Eastern Shelf of the Midland Basin (like most cratonic basins and platforms) exerts a strong influence on the geometry and spatial distribution of deltaic facies.

Elongate deltas.—Elongate deltas in North-Central Texas are typified by extensive progradation, relatively thick prodelta muds and preservation or storage of deltaic sands by subsidence. Deposition was probably more rapid and continuous than in lobate types. Subsidence of deltaic sands led to deposition of bar-finger deposits composed of abnormally thick superposed delta-front, channel-mouth-bar, and distributary-channel-fill sand (fig. 17). Because of the high degree of subsidence, mud lumps, mud diapirs, and highly contorted sands develop to deform the bar-finger deposits (fig. 18). These deltas display the greatest degree of progradation but it should be remembered that both lobate and elongate lobes may occur within the same system. The reader is referred to figures 16, 17, and 18 for a summary of the nature of environments and stratigraphy of facies in elongate lobes.

An idealized vertical sequence (upward) through an elongate lobe (fig. 20A) clearly demonstrates

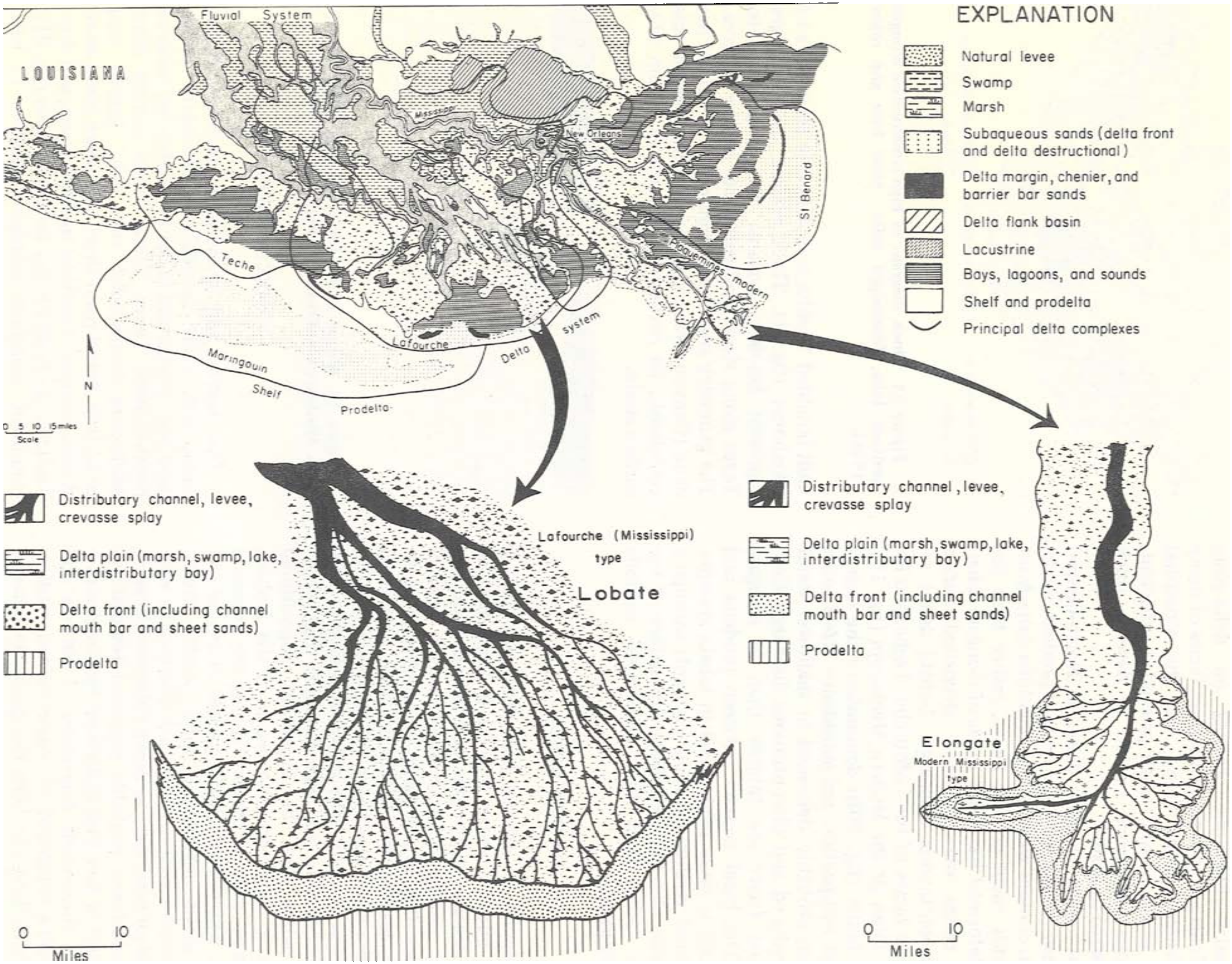


Figure 16. Plan view of principal depositional environments, high-constructive delta lobes, Mississippi delta. After Fisk (1944); from Fisher and others (1969).

the deformed nature of the progradational facies. Destructional facies are relatively insignificant with transgressive limestones resting on delta-plain facies. Coals occur in the delta-plain facies of many North-Central Texas deltas, but the structural stability of the tectonic shelf precluded sufficient, continuous subsidence needed to develop thick peat (marsh) deposits.

Lobate deltas.—Lobate deltas in North-Central Texas may be characterized by thin prodelta muds; they also contain well-bedded, sheetlike delta-front sands with small growth faults, rather than the highly deformed bar-finger sands of elongate lobes. Lobate deltas were probably deposited during slow, discontinuous discharge. Lobate deltas resemble the facies of the Lafourche, Teche, and St. Bernard lobes of the Modern Mississippi (fig. 19). Growth faults (fig. 20B) demonstrate the degree that mud compaction and subsidence affect lobes that were probably deposited in shallower water during reduced and discontinuous discharge. Constructional facies are thinner than in elongate deltas. The basal contact between prodelta and delta front is more gradational in lobate systems. An idealized vertical sequence (upward) through a lobate lobe (fig. 20B) illustrates the nature of the sheetlike delta front that commonly exhibits growth faulting.

Fan-Delta Systems

Fan deltas are alluvial fans that build into a standing body of water. The fan is dominated by braided streams, but marine destruction of the fan results in unique facies in which marine destructional bars of sand and gravel are interbedded with subaerial braided and fan-plain facies. McGowen (1970) described the facies and processes for this unique kind of delta. The system develops in areas with extreme relief and high gradients (figs. 8, 9).

Fan deltas may be important depositional elements in many cratonic basins of the faulted, yoked type, such as basins flanking the ancestral Rockies, where thick clastic wedges of arkose and arkosic gravel intertongue with marine facies. Coarse-grained clastic facies that intertongue with marine sequences, such as many Paleozoic facies in the Appalachians, probably represent braided fluvial systems or fans that underwent marine destruction with consequent deposition of barriers and strand plains composed of coarse-grained clastics.

Fan deltas have not been recognized in outcrop in North-Central Texas, but fan deltas did enter the basin from northern source areas located in the

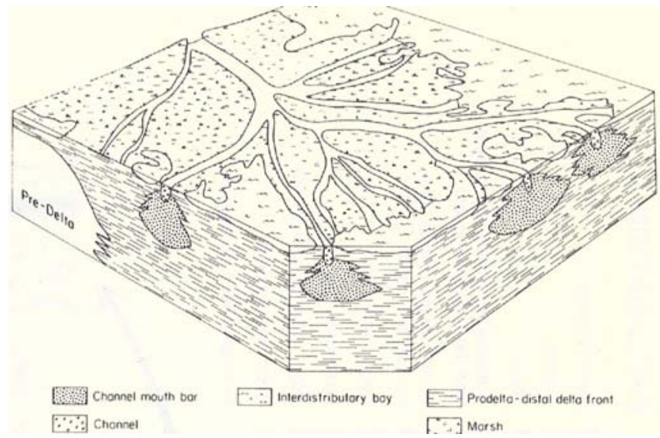


Figure 17. Block diagram of high-constructive elongate birdfoot lobe, Mississippi delta. After Fisk and others (1954).

fault-bounded Wichita and Arbuckle Mountains of Oklahoma (fig. 1). Thick arkosic clastic wedges represent fan-delta systems that prograded into Texas along steep gradients from nearby sources. The geometry and distribution of the Henrietta fan delta (Canyon Group) is described elsewhere in this guidebook; its occurrence is entirely within subsurface strata.

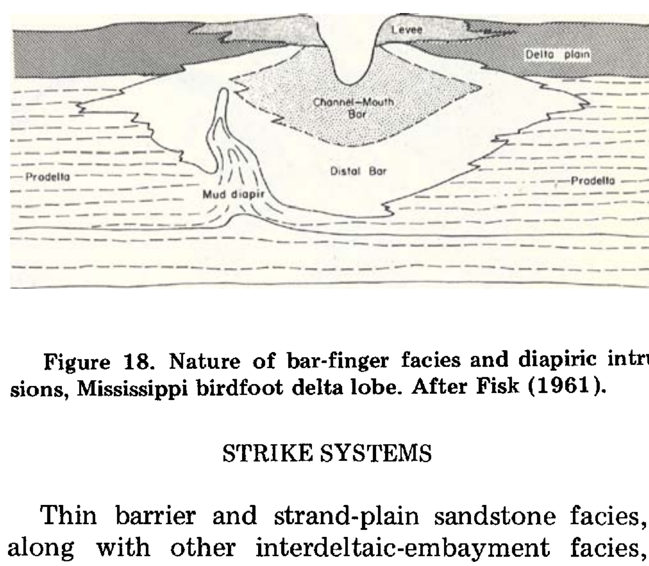


Figure 18. Nature of bar-finger facies and diapiric intrusions, Mississippi birdfoot delta lobe. After Fisk (1961).

STRIKE SYSTEMS

Thin barrier and strand-plain sandstone facies, along with other interdeltaic-embayment facies, have been recognized in the Pennsylvanian rocks of North-Central Texas. These facies include thick mudstones interbedded with thin, lignitic coal beds, thin strand-plain sheet and beach-berm sandstones, oxidized intertidal mudflat facies, and thin, fossiliferous, brackish-bay limestone beds (fig. 21). Dominant longshore transport appears to have been counterclockwise or southward along the North-Central Texas shorelines.

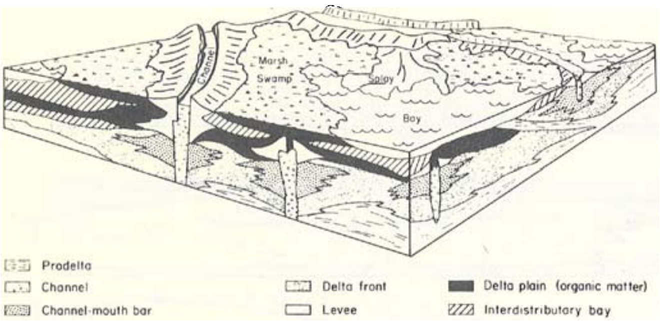


Figure 19. Block diagram of high-constructive Lafourche lobe, Mississippi delta. After Frazier (1967).

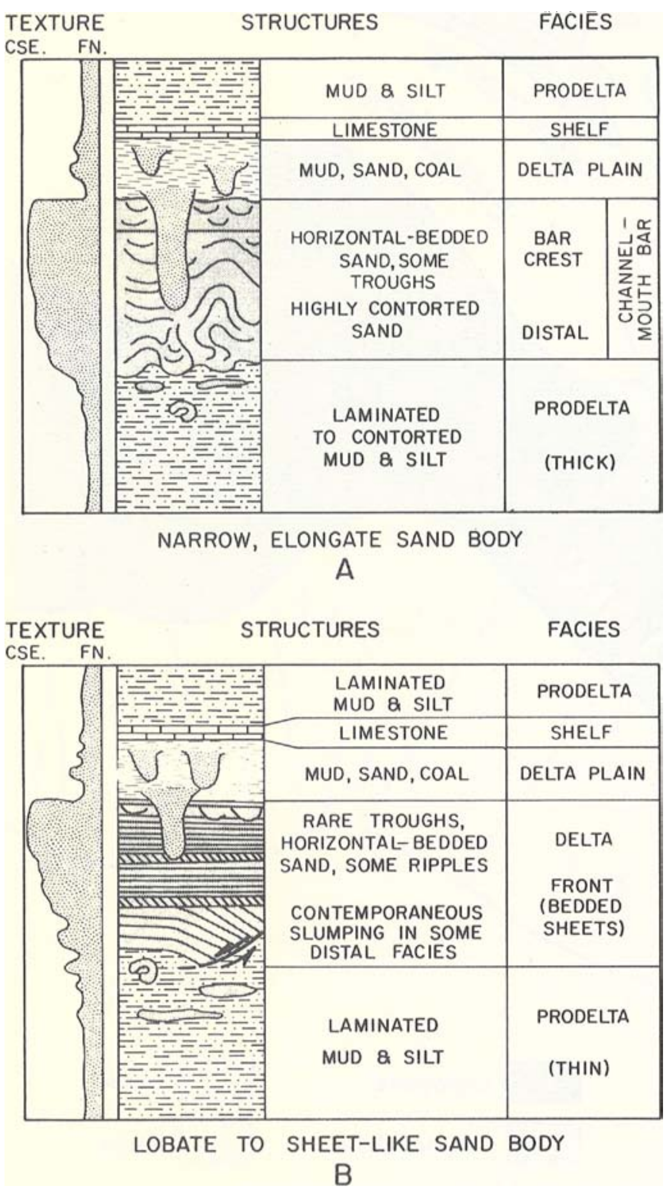


Figure 20. Idealized vertical sequences, deltaic systems in cratonic basins. A. High-constructive elongate delta. B. High-constructive lobate delta.

Perhaps the best modern example or model for the Pennsylvanian strike systems is the coastal zone of southwestern Louisiana and Texas. The bays, intertidal flats, and marshes adjacent to the Mississippi delta were described by Coleman (1966). Cheniers of the southwestern Louisiana coastline which resemble some Pennsylvanian strand-plain and berm facies were reported on by Gould and McFarlan (1959), while barrier-island genesis and internal structure have been considered by Bernard and others (1959, 1970). The reader should refer to these basic papers and a summary paper by LeBlanc (1972). Extensive references to strike systems have been compiled by Fisher and Brown (1972).

During delta progradation, sand and mud were transported laterally into delta-flank embayments and moved along shore into broad interdeltaic embayments (fig. 21). Regressive mudstones and marsh deposits accreted basinward over brackish-water limestones. During periods of diminished sediment supply resulting from shifting of a delta distributary, winnowing of the sediments resulted in thin strand-plain facies, beach berms, and other littoral sand deposits (fig. 22). Upon final delta abandonment, terrigenous clastic deposition in associated strike systems diminished and interdeltaic areas slowly compacted and subsided beneath transgressive shelf environments. Thin strand-plain or barrier sands accumulated during delta destruction, and coals were deposited in landward lagoons. As deltas foundered and interdeltaic embayments subsided, the thin barriers were successively abandoned and reestablished landward where relict sands were available from reworked delta facies. The relationship between deltaic deposition and genetically associated interdeltaic facies is illustrated on figure 22.

Most strike systems in North-Central Texas are thin, commonly beneath the resolution capability of E-logs. For this reason, subsurface mapping is difficult and only in outcrop has the nature of the facies been studied. Galloway and Brown (1972) described Cisco strike-fed systems.

Strike-fed facies include the following: 1) delta-flank mudstones, generally unfossiliferous, dark gray, rarely oxidized, subtidal, deposited by rapid accretion adjacent to delta source; 2) intertidal mudstones, oxidized, red, may be fossiliferous; 3) coal or lignite beds, commonly no root attachment, detrital, associated with plant-rich mudstones, occur landward of thin barriers and in isolated bays; 4) strand-plain and barrier sandstones, thin, display coarsening-upward sequence

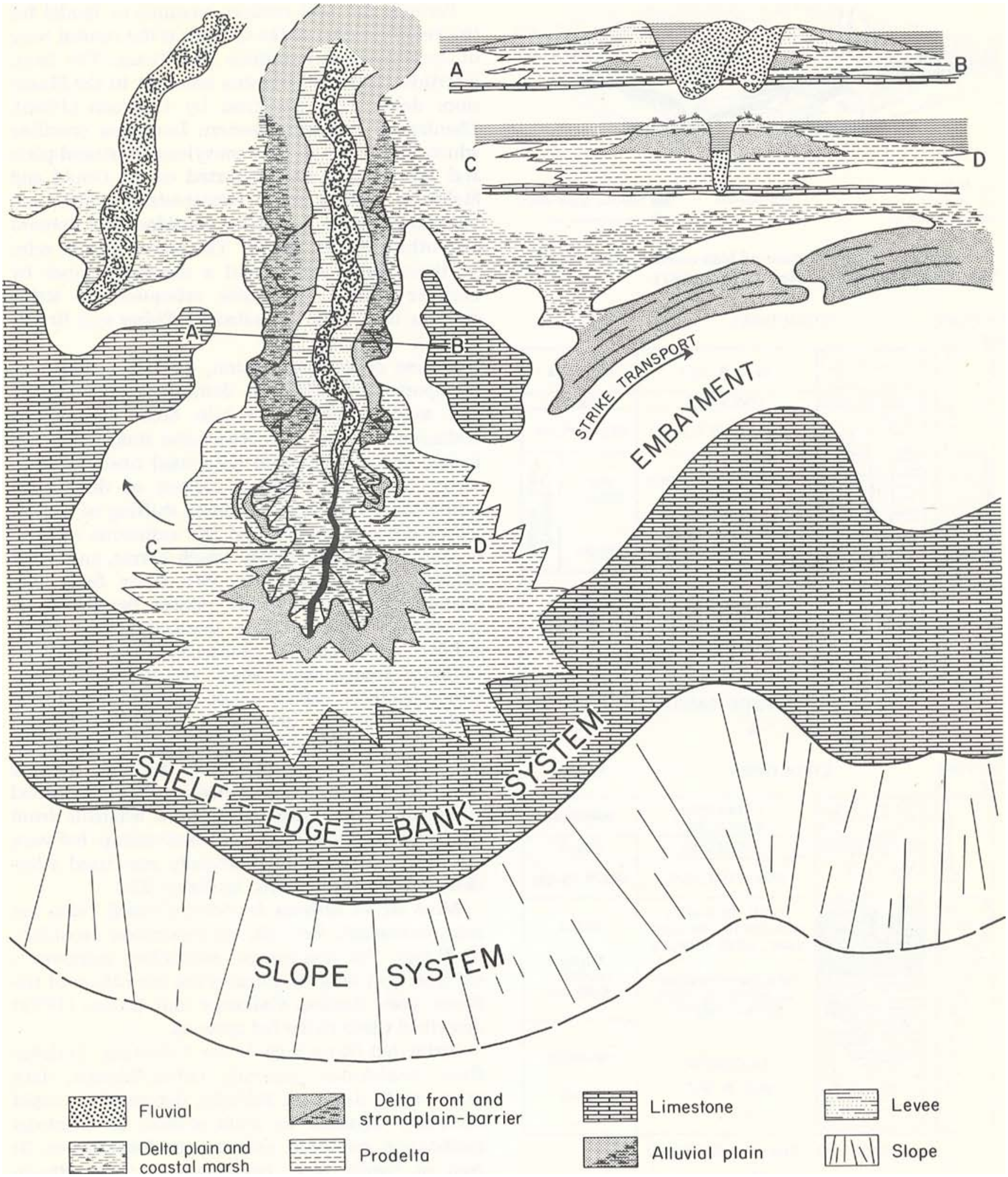


Figure 21. Generalized terrigenous clastic depositional model for cratonic basins. In part after Donaldson (1966, 1969) and Donaldson and others (1970).

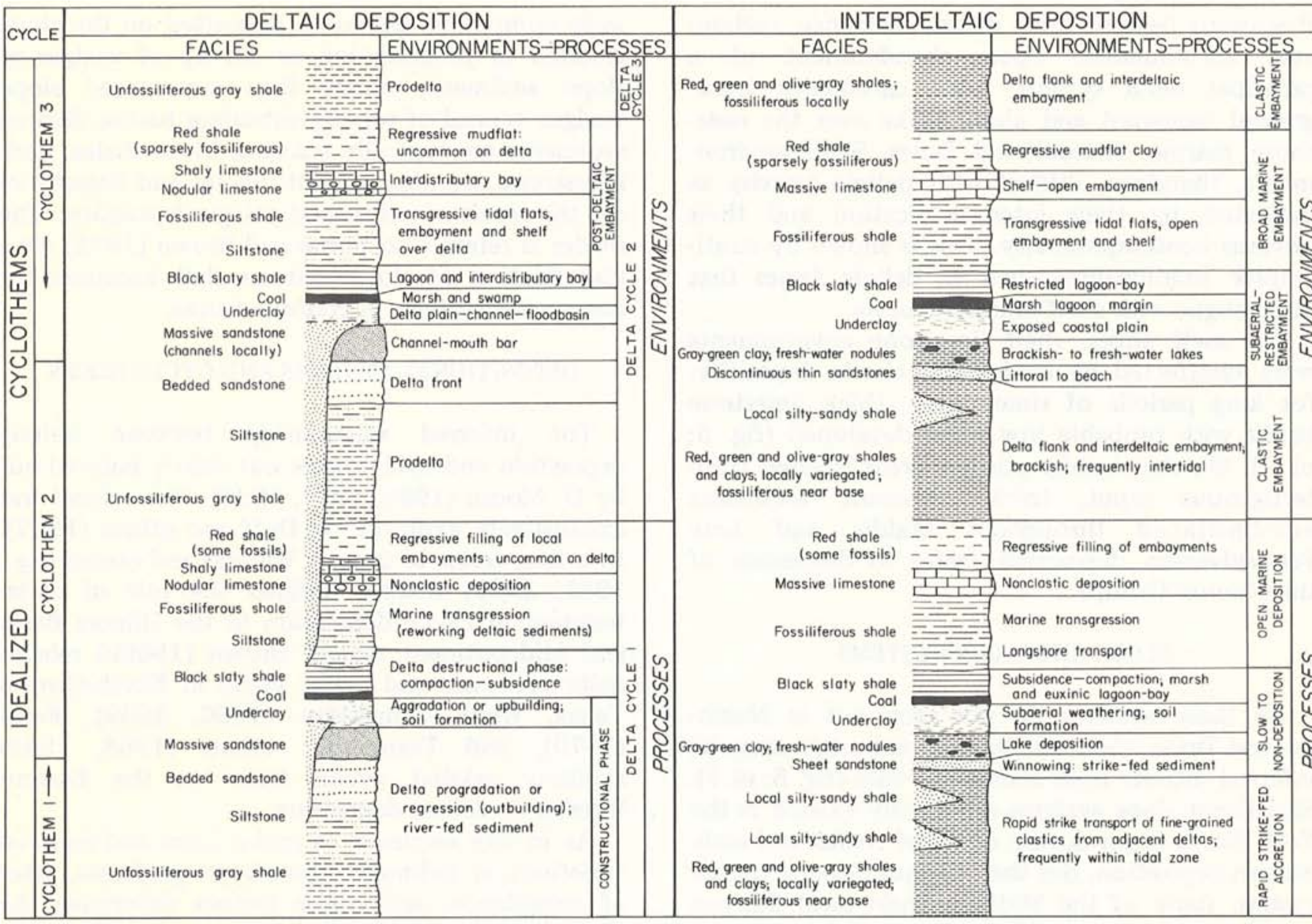


Figure 22. Inferred role of deltaic processes and environments in the deposition of cyclothems. Diagram based on idealized cyclothem (Weller, 1930; Wanless and Shepard, 1936).

from thin burrowed and wave-ripple-bedded units to massive beds with local beach or break-point bars with moderate-scale trough cross-beds and horizontal laminations; and 5) a variety of brackish-water limestones and fossiliferous mudstones that contain the most prolific mollusc-dominated assemblages in North-Central Texas. When properly understood, strike-fed systems supply considerable paleogeographic information about the basin and its paleodynamics.

SHELF SYSTEMS

Except for the outcrop of open-marine limestones and immediately adjacent thin, bioturbated, fossiliferous shales, no Strawn, Canyon, or Cisco shelf, slope, or basin facies crop out in North-Central Texas. As in most cratonic basins, slope and basin systems in the Midland Basin are deeply buried within basin fill; shelf limestones and bioturbated paralic mudstones are common along the edges (outcrop) of most cratonic basins and platforms (fig. 5; pl. I). If, however, a distinction is carefully drawn between structural shelf, physiographic shelf, and shelf environment, only a small percentage of cratonic basin sediments are probably of true shelf origin (i.e., deposited in equilibrium with shelf processes and environments). Within the North-Central Texas province, the Eastern structural shelf (or platform) supplied the tectonic stability during the Middle and Late Pennsylvanian for development of the physiographic shelf-slope-basin profile; terrigenous clastic sediments deposited on the Eastern Shelf are principally of paralic origin (deltaic, fluvial, and strike-fed nearshore facies). Bioturbated relict paralic sediments under shelf conditions, along with carbonate deposits, represent most of the true shelf facies.

Shelf carbonates and thin reworked and bioturbated relict paralic sediments developed in the absence of local input of paralic clastics (fig. 21).

Basinward beyond most deltaic influence, carbonates accumulated; upon abandonment of a principal delta system, these carbonates transgressed landward and along strike over the nearshore marine destructional facies. Shelf environments, therefore, shifted with deltaic activity as indicated by their interstratification and their obvious contemporaneity. This is shown by stratigraphic relationships such as deltaic facies that intertongue with shelf limestone units.

On shelf edges, shelf limestone environments were unaffected by terrigenous clastic deposition for long periods of time; there, thick limestone banks with probable low relief developed (fig. 5; pl. I). On structurally positive areas isolated from terrigenous input, thick carbonate sequences accumulated throughout Middle and Late Pennsylvanian deposition (refer to discussion of the Canyon Group).

SLOPE AND BASIN SYSTEMS

As these systems do not crop out in North-Central Texas, their distribution and origin must be inferred entirely from subsurface data (fig. 5; pl. I). Significant slope systems apparently existed in the Fort Worth Basin during much of Atoka and early Strawn deposition, but they did not develop on the eastern flank of the Midland Basin until Canyon and Cisco deposition (Van Siclen, 1959; Jackson, 1964), when acceleration of Midland Basin subsidence resulted in sufficient physiographic relief for slope environments to develop (pl. I).

Detailed studies of Cisco slope systems by Galloway and Brown (1972, 1973) indicate that the slopes prograded basinward in response to sediment supplied to the shelf edge by deltas and, perhaps, by tidal currents. The slopes were principally constructive; destructive features, aside from a possible submarine canyon, have not been recognized from subsurface data. Similar slope facies have been interpreted for a part of the Borden Siltstone of the Illinois Basin (Moore and Clarke, 1970); these facies are thought to be prodelta by Lineback (1969) and Swan and others (1965). Asquith (1970) recently interpreted slope facies within Upper Cretaceous rocks of the Rocky Mountain region.

Slope systems within cratonic basins were deposited by the same processes active in structurally unstable basins: principally turbidity currents, mass gravity movement, grain flow, and possible traction flow within slope channels. Because of the stability of the basin, however, the large compound fan-cones deposited on the slope resulted in progradation or off-lap of wedges of slope sediment, rather than superposed slope wedges typical of rapidly subsiding basins. Basinal sediments are typically siliceous black shales; dark limestones are also present. Shales and limestones are the result of pelitic and pelagic deposition. The reader is referred to Fisher and Brown (1972) for a classification of slope systems that accounts for deep-water systems in cratonic basins.

DEPOSITIONAL SYSTEMS AND CYCLOTHEMS

The inferred relationship between deltaic deposition and cyclothems was clearly pointed out by D. Moore (1958, 1959, 1966). The subject was exhaustively explored by Duff and others (1967). In a long series of papers, Wanless and others (e.g., 1963, 1970) sharply defined the role of delta-building in cyclic deposition in the Illinois Basin and Midcontinent region. Brown (1969b) related delta processes and cyclic facies in North-Central Texas, while Donaldson (1966, 1969), Ferm (1970), and Ferm and others (1968, 1969) similarly related cyclic facies in the Eastern Interior to deltaic deposition.

As in any sequence of rocks, local and regional variations in sediment, paleoslope gradients, rates of subsidence, and other factors determine the character of the cyclothem. All workers recognize the variability of "ideal" cyclothems (fig. 22); similarly, the variability of deltaic deposition is recognized by most workers. Because of the extreme stability of Pennsylvanian cratonic platforms and basins, the deltaic and interdeltaic sediments (fig. 22) are thin and regionally extensive. This factor has caused concern among some workers who wish to make direct geometric and scale comparisons of cyclothems and Modern deltaic sequences. A much better model in scale and geometry, as well as in process and environment, is a system such as the Texas Guadalupe delta (Donaldson, Martin, and Kanes, 1970) which is a high-constructive system that is building into a shallow bay in a relatively stable tectonic setting (fig. 21). Fluvial channels that prograde over thin deltaic facies, as in the Guadalupe delta, cut into subjacent deltaic facies in a manner similar to so many Pennsylvanian cyclothems (fig. 22) in which channels erode deeply into sediments of subjacent cycles. Use of a stable, cratonic-basin delta model (fig. 23) provides an interesting view of cyclothems; ideally, the many variations of cyclothems, such as the Piedmont cycle, the

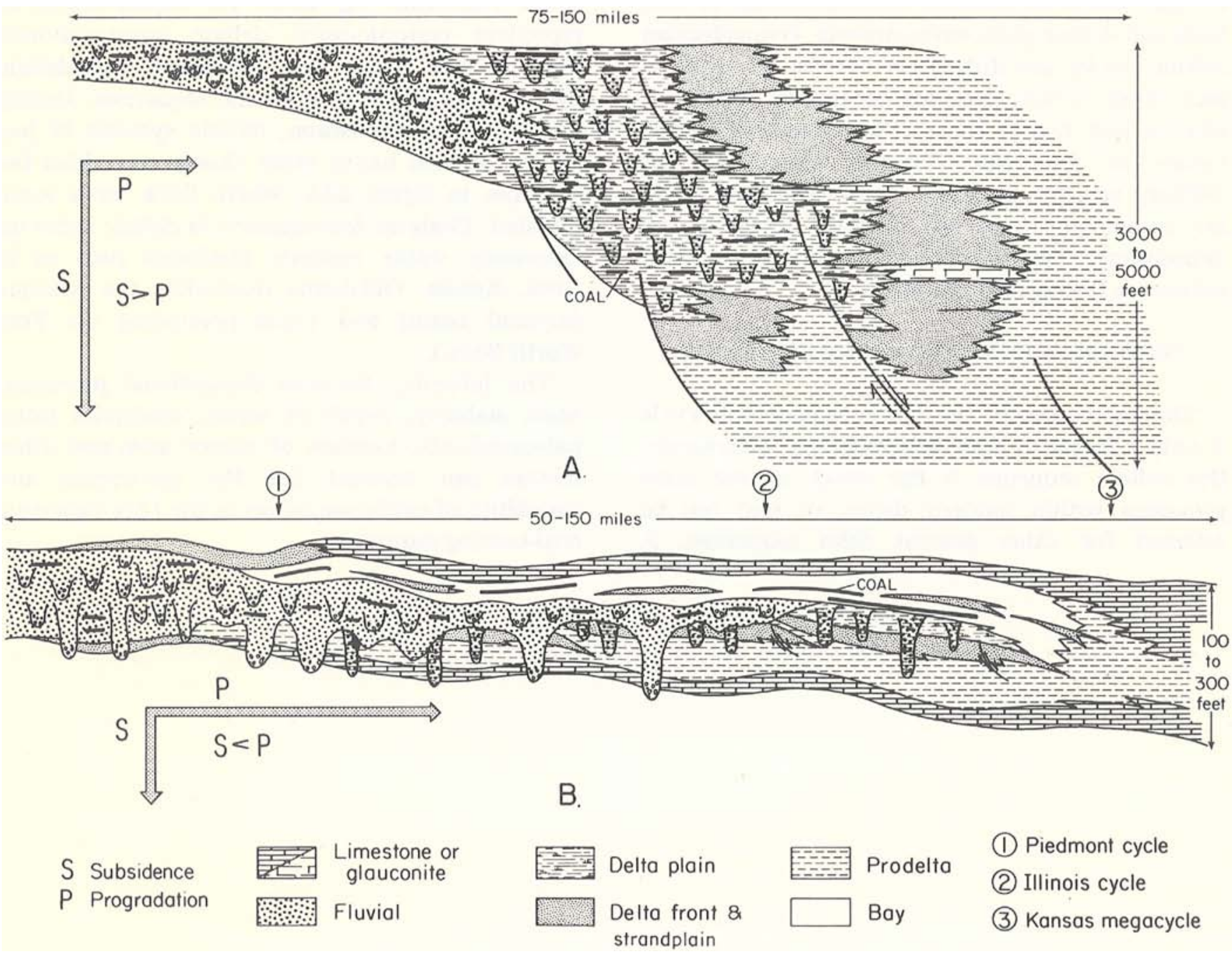


Figure 23. Comparison of fluvial-deltaic systems in differing tectonic settings. A. Rapidly subsiding basin. After Fisher and others (1969). B. Slowly subsiding basin (cratonic basin). In part after Donaldson and others (1969).

Illinois cycle, and the Kansas megacycle, can be explained within the context of regional variations in the facies tract of a delta system. If one considers the traditional cyclothem in terms of deltaic deposition (fig. 22), it can be seen that the delta cycle began with progradation whereas the cyclothem, by definition, began at the base of the sandstone member—either delta-front or channel-fill facies. Wanless and others (1969) and Donaldson (1969) showed the coincidence of coal beds and deltaic-plain environments. Pennsylvanian deltaic cycles are distinctive because of tectonic and other factors, but fundamentally (based on process and facies) they closely resemble deltaic cycles of Devonian, Triassic, Cretaceous, or Tertiary age, for example. If processes and facies are compared, there can be little doubt of the depositional nature of vast coal-bearing cyclic sequences throughout the world.

TECTONIC SETTING AND FACIES GEOMETRY

The uniqueness of the Pennsylvanian delta cycle is only a factor of scale and geometry. Genetically the deltaic sequence is the result of the same processes within modern deltas, or that can be inferred for other ancient delta sequences. A comparison of the scale, geometric, and spatial facies relationships between unstable basins and cratonic basins can be visualized in figure 23. With rapid subsidence, the basinward deltaic facies tract (fluvial-delta plain-delta front-prodelta) tends to stack vertically (fig. 23A); in a relatively stable tectonic setting, vertical storage or stacking of facies could not be accomplished and, therefore, deltas prograded rapidly and extensively across the stable platforms (fig. 23B). The superposition of repetitive cratonic-basin deltaic constructional-destructional cycles and associated interdeltaic cycles, resulted in cyclothemic sequences. During Pennsylvanian deposition, deltaic systems in less stable foreland basins more closely resembled the example in figure 23A, where thick coals accumulated. Coals are less common in deltaic facies on extremely stable cratonic platforms such as in Iowa, Kansas, Oklahoma (excluding the Arkoma foreland basin) and Texas (excluding the Fort Worth Basin).

The interplay between depositional processes, basin stability, depth of water, sand/mud ratio, paleogradients, location of source area, and other factors can account for the occurrence and variability of cyclic sequences in the Late Paleozoic coal-bearing sequences.

DEPOSITIONAL SYSTEMS IN THE UPPER STRAWN GROUP OF NORTH-CENTRAL TEXAS

Arthur W. Cleaves II[2]

REGIONAL RELATIONSHIPS

The Strawn Group comprises a thick sequence of Middle Pennsylvanian (Desmoines Series) terrigenous clastic and carbonate facies that crop out in a narrow, partially covered band across North-Central Texas. Cretaceous overlap breaks the band into several discontinuous areas of outcrop, the two largest being in the Colorado River valley (San Saba, Brown, and Mills Counties) and in the Brazos River valley (Parker, Palo Pinto, Erath, and Eastland Counties). In this report, the surface geology will be discussed only for the outcrop zone within the Brazos River valley (fig. 4).

Exposed Strawn rock units comprise terrigenous clastic facies—shale, sandstone, and conglomerate almost exclusively—with carbonate facies making up less than 5 percent of the total.

The rocks strike N 41° E and dip about 1° NW through most of Palo Pinto County. The strike is N 20° E from southern Palo Pinto County to the Colorado River and is N 75° E east of Palo Pinto County.

The Strawn Group has been studied to date in the subsurface using approximately 1,400 electric and sample logs. The area includes eight counties and about 7,000 square miles. Net-sandstone thickness maps have been prepared for three stratigraphic intervals (figs. 27, 28, and 29). Each of the Strawn field trip localities is within one of these intervals.

In the broadest sense, the Strawn terrigenous clastic facies can be divided into two general units on the basis of tectonic setting and lithofacies character (Turner, 1957). The lower Strawn sequence is similar to the underlying Atoka Group in lithology and distribution. The Atoka and lower Strawn constitute basin fill for the Fort Worth Basin and were not deposited beyond the western flank of the basin (fig. 5). Fan deltas and slope depositional systems (including turbidite deposits) make up most of the basin fill. To the west the temporal equivalent of these basin-fill units is the Caddo carbonate-bank depositional system (Turner, 1957)—200 to 500 feet of limestone and dolomite that developed on the Concho Platform (fig. 1).

The upper part of the Strawn Group is younger than the Caddo carbonate system and is related to the Canyon and Cisco in terms of depositional history and facies represented. By the time the Meek Bend Limestone was deposited, Strawn sediments had completely filled the Fort Worth Basin and were being deposited on the Concho Platform to the west (fig. 5). Fluvial and deltaic systems of the Buck Creek and Dobbs Valley sandstones (post-Meek Bend) prograded more than 80 miles beyond the western flank of the Fort Worth Basin. Inasmuch as the Midland Basin was not a deep basin, no major slope depositional systems developed in the upper Strawn, for there was no significant break in slope on which to localize the accumulation of deltaic sediment. Slope deposition did not become significant on the western margin of the platform until the Midland Basin had undergone considerable subsidence. Slope systems in the region are discussed in a section on the Cisco Group, and by Galloway and Brown (1973).

UPPER STRAWN FLUVIAL-DELTAIC DEPOSITIONAL SYSTEMS: EXAMPLES

The upper part of the Strawn Group is made up of a variety of distinctive fluvial, deltaic, and marine shelf depositional systems. Eight separate deltaic progradational cycles are recorded at the surface and in the shallow subsurface of the eight-county study area. Rather than discuss all of the systems in this thick sequence, three representative stratigraphic units have been selected that typify the surface and subsurface character of upper Strawn facies. The intervals include: 1) Dobbs Valley Sandstone, 2) upper Mingus Shale, and 3) Brazos River Formation. All of the Strawn field localities in this guidebook are within these intervals.

Dobbs Valley Sandstone

The Dobbs Valley Sandstone is what might informally be termed the middle "member" of the Mingus Formation. It is underlain by a thick sequence of shallow shelf and prodelta muds (fig. 24). Above the Dobbs Valley Member are the Goen Limestone, Thurber Coal, and a delta-plain and prodelta shale unit. In the subsurface, the Jennings Sandstone is probably the stratigraphic equivalent

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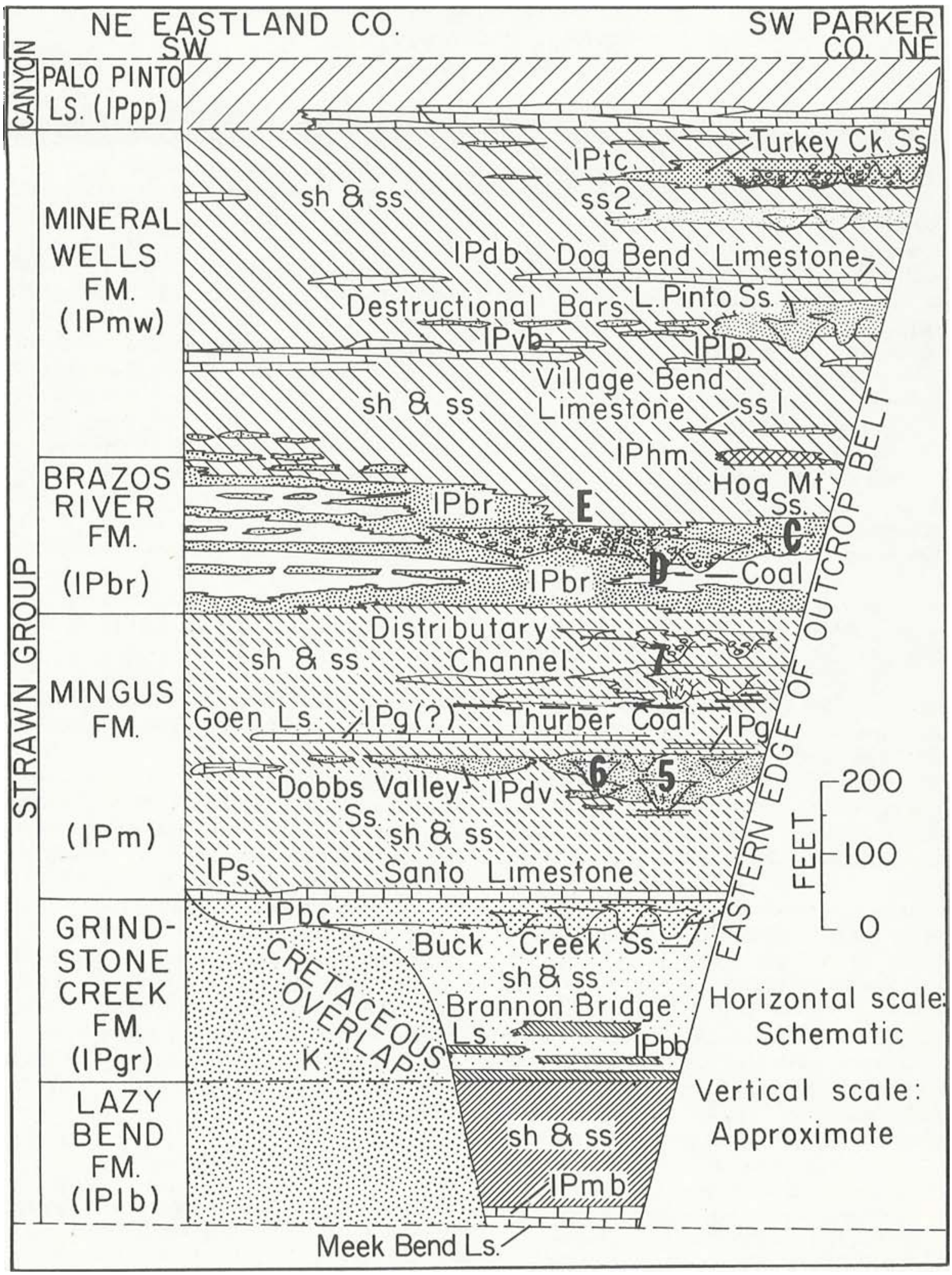

Figure 24. Schematic facies cross section along outcrop, Strawn Group, North-Central Texas. Adapted from Abilene Sheet, Texas Geologic Atlas (1972).

of the Dobbs Valley Sandstone (Brown and Goodson, 1972).

In outcrop, the Dobbs Valley Sandstone consists of small high-constructive lobate delta lobes. The deltaic facies is best exposed south of Mineral Wells near the town of Bennett, Parker County. In that area, a complete vertical sequence of progradational facies is preserved in highway and railroad cuts; progradational facies will be considered in detail. Progradational facies include: prodelta, distal delta front, proximal delta front, channel-mouth bar, interdistributary bay, and distributary channel. Textural characteristics and sedimentary structures of the deltaic sandstone and mudstone facies are shown in figure 39.

A thick *prodelta* mudstone sequence (30 to 40 feet) underlies the delta-front facies of the Dobbs Valley Sandstone in its northeastern outcrop area. Prodelta sediments are for the most part finely laminated, plant-rich mudstones. Finely macerated fibrous plant material ("coffee grounds") is the main organic constituent of the facies. Absence of macrofauna and burrows typifies the prodelta facies at Locality 5 (Bennett); in very thin (10 to 20 feet thick) sequences, however, organisms commonly bioturbate the sediment to the extent that the prodelta or even the distal delta-front facies cannot be distinguished from shallow-marine shelf sediments.

In major deltaic systems, the *proximal delta-front* facies also may contain small slump blocks, flow rolls, and thin, continuous flaggy beds of silt or very fine sandstone. Slump blocks and flow rolls are transported with varying amounts of internal deformation from the shallow-water channel-mouth bar or proximal delta front into deeper water during periods of high discharge. In contrast, the flags are deposited either from suspension or from locally generated turbidity currents. Graded beds, however, are difficult to detect because of the well-sorted nature of delta-front sands.

Distal delta front is a distinctive facies in thicker deltaic systems; the coarsening-upward progradational sequences are prominent. Distal delta-front facies do not, however, occur in thin deltaic sequences (for example, a small delta prograding into a shallow, protected bay) or on the protected flanks of larger delta complexes where both progradation and marine reworking are minimal. The distal delta front is a significant facies at Locality 5B; the facies cannot be distinguished from the proximal delta front that is exposed at Locality 5A. Locality 5B is adjacent to the main axis of progradation for the deltaic lobe. On the other hand, 5A is offset from the main axis; it received far less total sediment; and it shows very little evidence of marine reworking.

The distal delta front at Locality 5B is characterized by interbedded units of lignitic, silt-rich mudstone and flaggy, very fine sandstone. There is a gradual upward increase in total sand, with sandstone flags becoming more numerous, thicker, and closer together; at the same time, mudstone units become thinner until they are only partings between thick sandstone bodies. Individual flags are thin, rarely exceeding 2 inches. They commonly exhibit a wave-rippled upper surface, lack evidence of burrowing, and may contain small-scale trough cross-beds. Marine reworking is clearly the dominant process on the lower delta front.

Higher in the delta-front sequence at Locality 5B, wave-rippled sandstone flags are replaced by thicker sandstone units that are largely horizontally laminated. Small- to medium-scale trough cross-beds are also common and some oscillation ripples occur on the upper surfaces of some horizontally laminated sandstone units. Deposition of this proximal delta facies occurred in shallow water adjacent to the channel-mouth bar. Fluvial processes, especially active during times of peak discharge, have eliminated the effects of marine reworking and suppressed the activities of burrowing organisms. The rate of sedimentation near the channel mouth was too rapid for infaunal, burrowing organisms to survive.

The *channel-mouth bar* is a significant and distinctive facies in high-constructive elongate and lobate deltaic depositional systems in the Pennsylvanian of North-Central Texas. Within high-constructive elongate systems, for example the Perrin delta system described elsewhere in this guidebook, the channel-mouth bar may be 50 feet thick and may be highly contorted (see fig. 20A). At Bennett, in contrast, the Dobbs Valley channel-mouth bar is about 25 feet thick and exhibits almost no plastic deformation. The channel-mouth bar at Locality 5B (fig. 63) is made up of massive, well-sorted, blocky sandstone units. Horizontal lamination, formed under upper flow-regime conditions in very shallow water, is the dominant sedimentary structure. Elongate, low-angle, large-scale troughs slice into the channel-mouth bar at many points along the outcrop and represent scours eroded into the bar crest during floods.

Locality 5A is less than 0.5 mile from Locality 5B, but its *delta-front* facies are considerably different. Due to intense burrowing by infaunal organisms, sediments of the delta front have been thoroughly bioturbated. No distinct channel-mouth bar is present, because the local distributary was not feeding a significant volume of sediment to the northeast at that time. The finer sediment (coarse siltstone), carbonate cement, and the lack of abundant wave-rippled flags at 5A suggest deposition lateral to the main axis of progradation, perhaps within an embayment shielded from many of the effects of marine reworking. A slow sedimentation rate and protection from marine reworking of the delta front furnished a hospitable environment for a burrowing infauna that obliterated most of the primary sedimentary structures in the delta front.

One of the most significant aspects of the deltaic sequence seen at the 5B Bennett locality is the prominent *growth faulting* developed in the delta-front and channel-mouth bar facies (fig. 63). These faults formed in response to sediment loading at the crest of the channel-mouth bar. They cut the delta front into a series of slump blocks; each block has been rotated so that the sandstone beds dip toward the fault plane (fig. 63A, C). Fault movement was slow, but took place during the entire period of local channel-mouth-bar deposition. Evidence for contemporaneous deposition and faulting is the fact that the proximal delta front and the channel-mouth bar thicken along the fault plane in the down-faulted block. A similar type of phenomenon has also been described for Locality 9 in the Avis Sandstone (Cisco Group).

Rate of deposition of a progradational sand body has a significant influence on how the sand body will deform when deposited upon a thick sequence of water-saturated mud. The delta-front sandstone section exposed at Bennett was deposited in small increments. This allowed a fault, once formed, to move gradually in response to slight overloading at the distributary-mouth bar, permitting a thicker down-faulted section to develop. Rapid and excessive overloading of the bar would initiate more rapid movement along a fault and perhaps could even sever a slump block from the rest of the delta front.

In contrast to the slow deformation described above for the delta front of a high-constructive lobate delta is the more rapid deformation that can occur with the rapid progradation of a high-constructive elongate delta bar finger. Avulsion of a distributary would release a large quantity of sand to be deposited rapidly along a narrow trend on top of the thick section of poorly compacted, water-saturated mud. Rapid loading of the mud would cause some of it to move laterally from beneath the sand. The sand could then deform plastically through part or all of its thickness. Highly contorted bases are characteristic of modern bar-finger sands of the Mississippi River (fig. 20A), as well as of those preserved in the Pennsylvanian (Optional Locality H; King Sand, Cisco Group).

Overlying the delta-front facies of the Dobbs Valley Sandstone in the Bennett area are an interdistributary-bay mudstone and a distributary-channel sandstone. The *interdistributary-bay* mudstone is less silty and lacks the laminations and detrital coal seams noted in the Mingus Formation at Lake Palo Pinto. In addition, the macrobiota consists of crinoid ossicles, whole and broken large spiriferid brachiopods, and fibrous plant hash. The burrowed, unlaminated mudstone and the presence of stenohaline marine organisms both suggest deposition in an open bay of nearly normal salinity.

Outcropping *distributary channels* in the Dobbs Valley Sandstone are similar in overall scale and sedimentary structures to the Mingus channel-fill facies at Lake Palo Pinto spillway. The Dobbs Valley channel facies overlying the bay mudstone at Locality 5A is deformed at the base and cuts through the mudstone to the subjacent delta-front siltstone. Abandonment of this distributary and subsidence of the Bennett deltaic lobe gave rise to marine reworking of the sand and deposition of the Goen Limestone. The smaller, symmetrical channel at Locality 6 is almost wholly composed of large-scale troughs at the base and small-scale troughs and ripple-drift cross-laminations higher. The channel is constructed of vertically aggrading sandstone units rather than laterally accreting units, which are more characteristic of point-bar deposits.

At the close of the delta deposition, the local delta lobe at Bennett was abandoned through avulsion of the trunk distributary. Sedimentation could no longer keep pace with the slow but continuous subsidence of the deltaic sands into the subjacent prodelta muds. As a result, a gradual local marine transgression brought about marine reworking of the uppermost part of earlier deposited distributary channel sands; a fossiliferous shelf mudstone was deposited on top of the entire deltaic sequence. The Goen Limestone represents the reworked delta-plain facies that marked the close of the Dobbs Valley deltaic cycle.

Deltaic lobes present in central and western Palo Pinto County (fig. 27) do not constitute the main

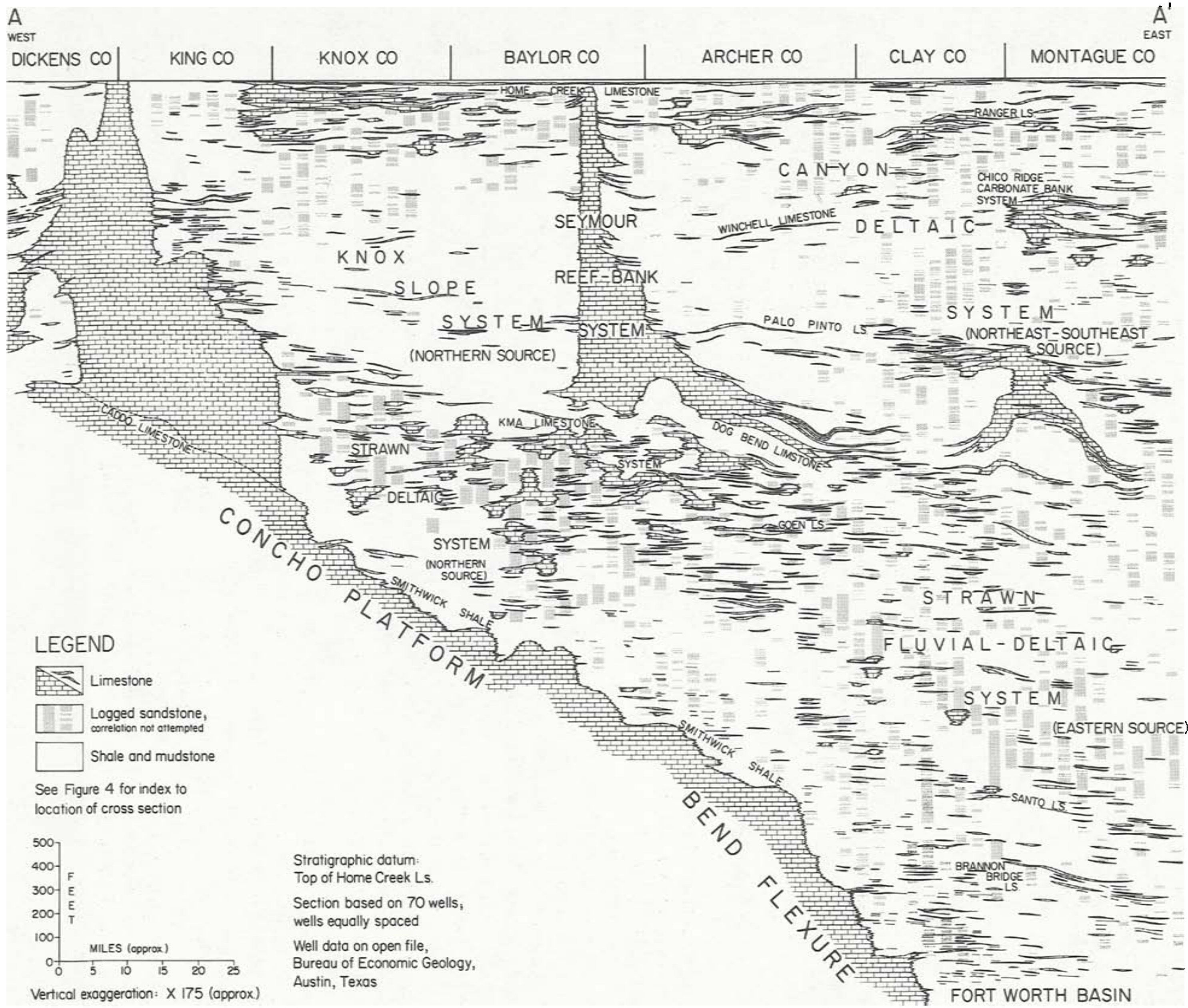

Figure 25. Subsurface cross section A-A′ (dip) from Dickens to Montague Counties, Texas, showing facies of the upper part of the Strawn and all of the Canyon Group. Section based on 80 wells. See fig. 4 for line of section. Data on open-file, Texas Bureau of Economic Geology.

zone of deltaic progradation. The Bennett delta complex built into a shallow, delta-flank, marine embayment. This embayment was largely a bypass area for the larger deltaic complexes to the north, west, and southwest. The northern deltas were fed from a major fluvial system in eastern Wise and Montague Counties. They prograded downdip westward and southwestward for more than 100 miles and their deposits interfingered with the younger elements of the Strawn Caddo carbonate platform (figs. 5, 25). The downdip progradation of the Dobbs Valley (Jennings) and the underlying Buck Creek (Gardner) sandstones constitute the westernmost progradation of Strawn or Canyon delta systems fed by the Ouachita foldbelt. Later systems prograded less extensively; thick carbonate units border later Strawn and Canyon delta systems on the basinward side. The Dobbs Valley Sandstone furnished a stable platform on which subsequent Strawn and Canyon carbonate-bank systems were constructed.

Upper Mingus Shale

The upper part of the Mingus Shale, in outcrop, comprises small, bay-head deltas, shelf-embayment mudstones, and the prodelta shale for the overlying Brazos River (Sandstone) delta system. In its northern outcrop area, the upper Mingus Formation contains small lobate deltas. These delta systems underwent very gradual subsidence, due largely to compaction of the underlying mudstone. As a result, some of these lobate deltas have preserved a complete suite of delta-plain facies. Farther south along the trend of the outcrop, sandstone is almost absent in the upper part of the Mingus Formation. A bituminous coal unit, the Thurber Coal, crops out near the base of the formation.

Deltaic facies of the upper Mingus are best exposed in road and spillway cuts at the east end of Lake Palo Pinto and along the base of the Brazos River Sandstone escarpment (Dry Creek) in western Parker County. For purposes of this report, the facies exposed near Lake Palo Pinto will be described in greater detail.

Deltaic facies exposed near Lake Palo Pinto include reworked delta-front sands, lignitic interdistributary mudstone, distributary-channel deposits, lignitic delta-plain mudstone, and fine-grained meanderbelt point-bar sandstone. The delta front is a marginal facies of a small lobate delta; it was deposited along strike from the main deltaic distributaries. The delta front is characterized by wave-rippled, flaggy, calcite-cemented, very fine sandstone. Marine reworking was slow enough to allow infaunal organisms to burrow the sediment, but not slow enough to permit complete bioturbation.

A thin, laminated, silty interdistributary-bay shale separates the delta front from overlying sandstone units in the Lake Palo Pinto area. It is fossiliferous near the base and contains a sparse fauna of gastropods and bivalves; microfossil analysis would probably reveal a more diversified assemblage of foraminifers, ostracods, and plant spores. Three zones of lignitic coal crop out in the shale; the lower two are detrital, inasmuch as plant debris is finely macerated, fibrous material that is oriented parallel to bedding. The absence of root casts in the underlying shale is additional evidence that plant debris did not accumulate *in situ*. The third (upper) coal unit also probably had a detrital origin, for it contains charcoal seams formed from the carbonization of woody material; it occurs in the siltstone of the top 2 feet of the bay facies and directly underlies the wood-choked base of a distributary channel. The charcoal seams and the siltstone may have been deposited during an early stage in the avulsion of the distributary and thus are genetically linked to the distributary channel and not to bay sedimentation.

The distributary channel-fill deposit at Lake Palo Pinto locality has an erosional base that cuts into the underlying interdistributary-bay mudstone. In the center of the spillway, it has scoured into the alternating flaggy, burrowed sandstone and siltstone at the top of the delta front. Sedimentary structures include dominant large-scale trough cross-beds in the lower part of the channel and small-scale trough cross-beds and ripple-drift cross-laminations above. Little compactional deformation has occurred where the channel has cut into the delta front, but along the roadway, where the bay mudstone is 9 feet thick, compaction has largely obliterated primary sedimentary structures in the lowest 5 feet of the distributary deposit. Also, this basal zone in the road cut is choked with the casts from logs of *Calamites*, *Lepidodendron*, and other tree-forming seed ferns. Apparently, when avulsion shifted the channel across the interdistributary bay to a new area of progradation, the channel swept up coarse woody debris from swamps on the lower delta plain.

After the distributary channel that is preserved in the spillway was first abandoned, it was reoccupied from time to time during periods of flooding. Numerous small-scale trough cross-bedded sandstone and siltstone flags present on the

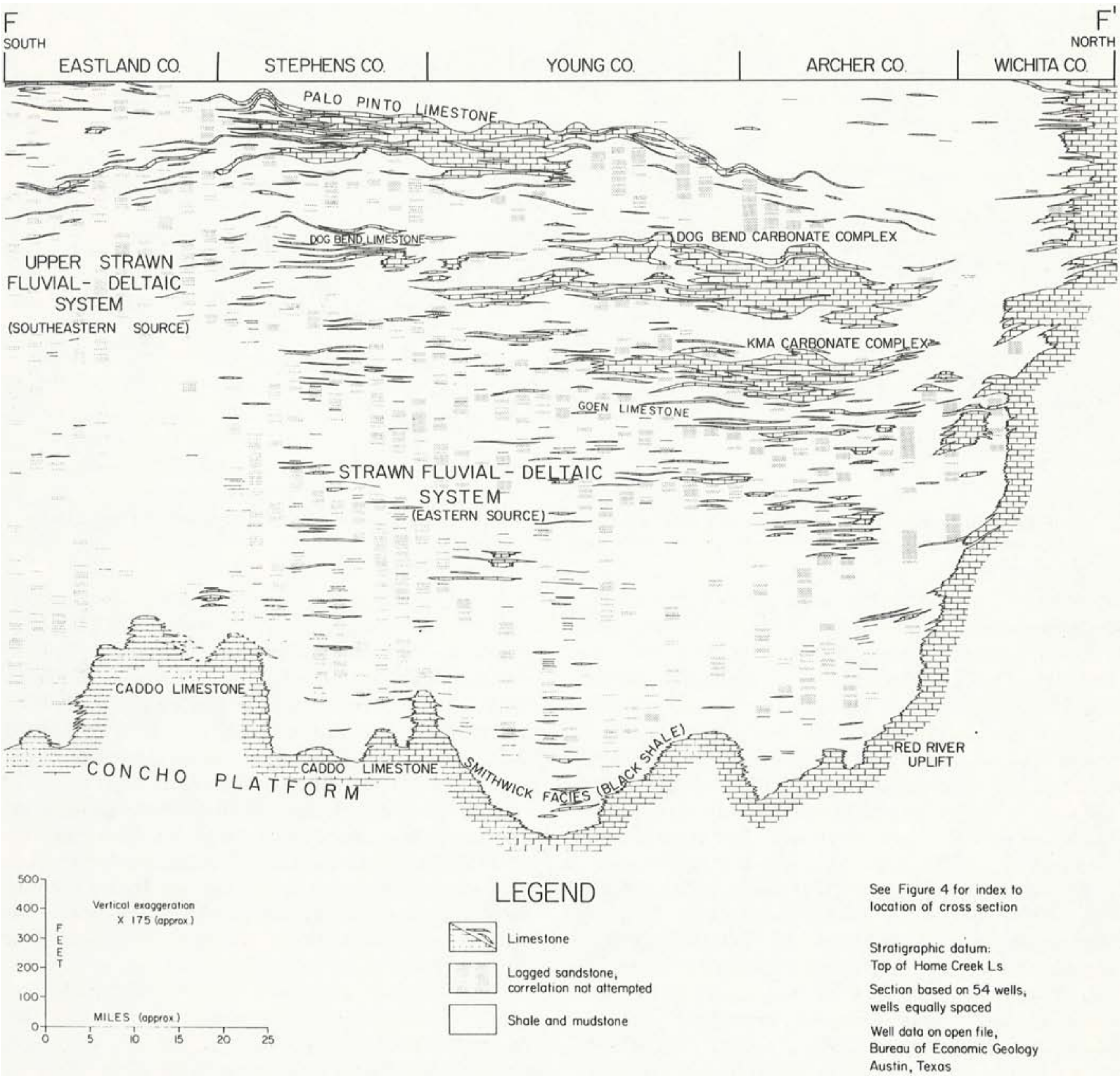

Figure 26. Subsurface cross section F-F′ (strike) from Eastland to Wichita Counties, Texas, showing facies of the Strawn Group. Based on 53 wells. See fig. 4 for line of section. Data on open-file, Texas Bureau of Economic Geology.

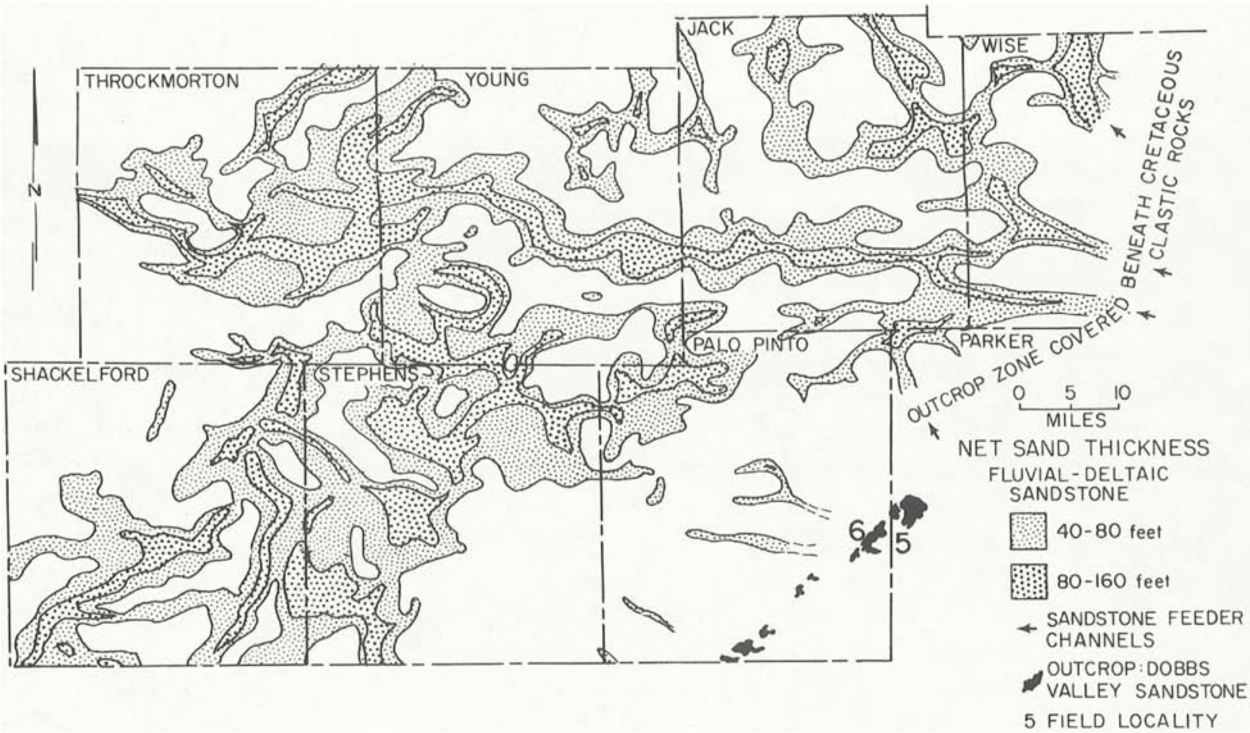

Figure 27. Net-sandstone map of the Dobbs Valley Sandstone, North-Central Texas. Subsurface control based on 1,300 wells; data on open-file, Texas Bureau of Economic Geology.

spillway flat near the dam were deposited on such occasions. For most of the time, however, silt, clay, and organic debris settled out from suspension in the ponded water of the abandoned distributary. With the slow but continuous subsidence of the deltaic lobe, marine burrowing organisms invaded the lower reaches of the abandoned distributary and reworked portions of the sediment. Thus, the complete channel-fill suite contains burrowed, current-rippled fine sandstone, silty lignite, and laminated plant-rich mudstone.

Subsurface mapping of that part of the Mingus Formation above the Goen Limestone demonstrates that the main thrust of deltation during Mingus deposition was in Jack and Young Counties (fig. 28). The source area for this high-constructive elongate and lobate complex was the Ouachita Mountain front in the area between Dallas and Sherman, Texas (figs. 1, 5). Beyond the western fringes of the deltaic system (Haskell, Throckmorton, and Shackelford Counties), the first of several carbonate banks developed on a stable platform established by the subjacent Dobbs Valley deltaic complex (figs. 5, 25). The composition and facies relationships of these carbonate systems are described in detail within the Canyon Group report (this guidebook).

South of the main upper Mingus sand trends, in western and northern Palo Pinto County (fig. 28), sedimentation was principally in a large interdeltaic embayment. Deposition of the Thurber Coal took place in the swamps and marshes of this shallow marine bay. Distribution of the underlying Dobbs Valley delta system in this area suggests that the coal deposits in the northeastern part of the county may have formed in fresh-water swamps on the delta plain. Farther to the south, however, the coal occurs in a major delta-flank embayment. This interpretation is supported by the presence of a thin band of calcareous siltstone containing marine fossils just above the coal in the Strawn area (Plummer and Hornberger, 1935).

The Thurber Coal is the only North-Central Texas coal unit that has been successfully developed commercially. It was mined in southwestern Palo Pinto County from 1885 to 1920 to serve as fuel for the Texas and Pacific Railway (Plummer and Hornberger, 1935). The unit is a low-grade bituminous coal that has a high sulfur and ash content. It attains a maximum thickness of 36 inches in northwestern Erath County south of Thurber and has an average thickness of about 24 inches in the shallow subsurface beneath Mingus and Strawn. Its outcrop in most places is concealed

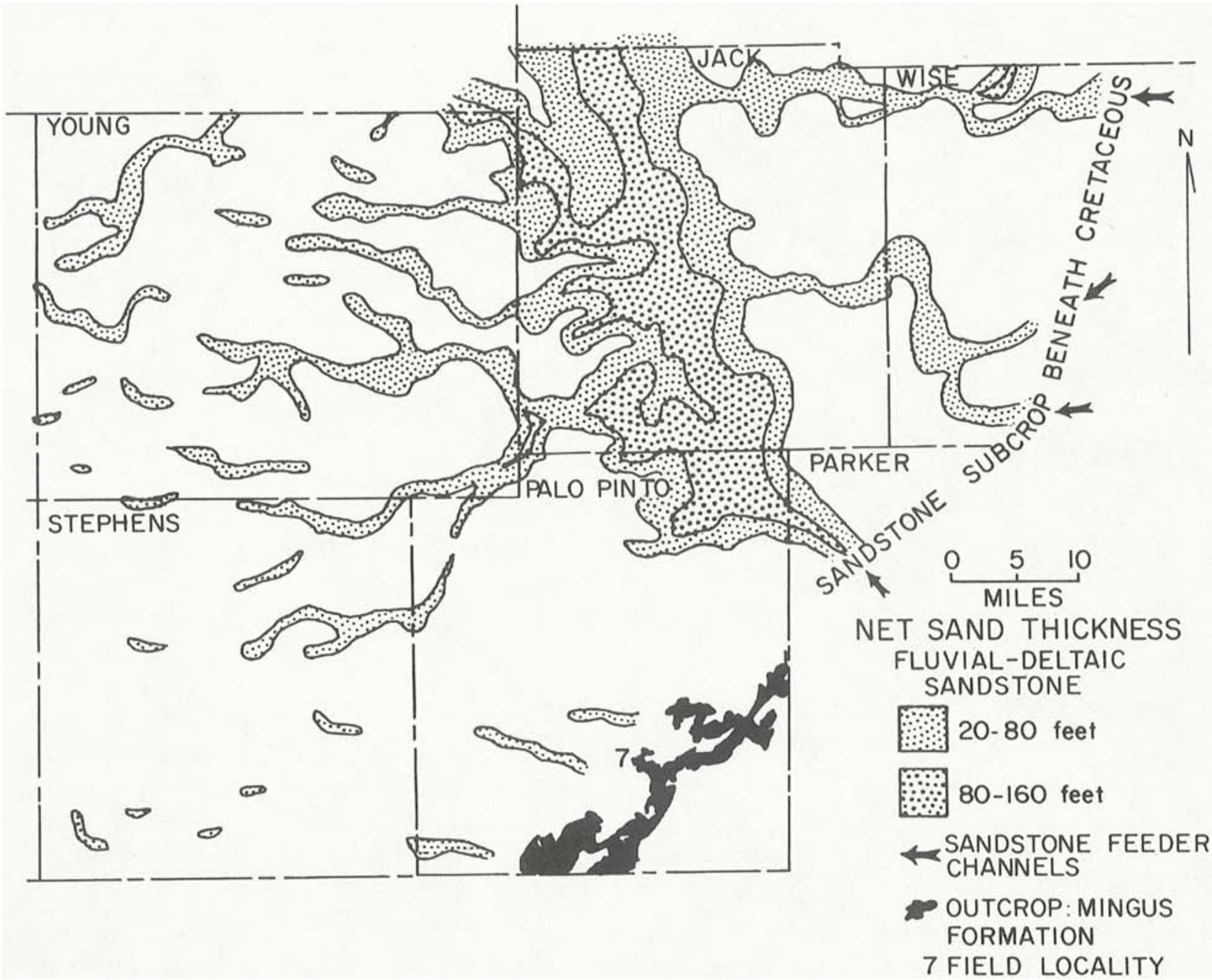

Figure 28. Net-sandstone map, upper part of the Mingus Formation, Strawn Group, North-Central Texas. Subsurface control based on approximately 1,300 wells; data on open-file, Texas Bureau of Economic Geology.

by talus from the mudstone and sandstone flags of the Brazos River escarpment.

The Thurber Coal is widespread in Palo Pinto and adjacent counties (fig. 30). Unfortunately, it is an economically feasible target for strip mining only near its outcrop area near Thurber. Also, the coal's sulfur content is too high to meet present federal pollution standards.

Brazos River Formation

The Brazos River Formation forms a steep, scenic escarpment across the southern half of Palo Pinto County from Mineral Wells to Thurber. In the northeastern part of the outcrop belt, the formation has three distinct facies. The lowest unit is a delta-front sandstone of a lobate delta system. This 20 to 50 feet of fine, carbonate-cemented sandstone consists of thin flags containing small-scale trough cross-beds, climbing ripples, and horizontal laminations. Symmetrical ripples are present on the surfaces of many of the flags; burrows are rare. These delta-front sandstones have been reworked along strike by marine processes to the extent that a distinct channel-mouth-bar facies is virtually absent. Instead, there is a sheet sand that extends along strike in the outcrop belt for more than 20 miles. Small channel-mouth bars apparently were laid down and preserved only right at the mouth of individual distributaries.

The middle Brazos River facies is a gray, laminated interdistributary-bay mudstone similar in all respects to the same facies exposed in the Lake Palo Pinto spillway (Locality 7). It contains a thin zone of detrital lignitic shale and a sparse fauna of marine gastropods, bivalves, and brachiopods.

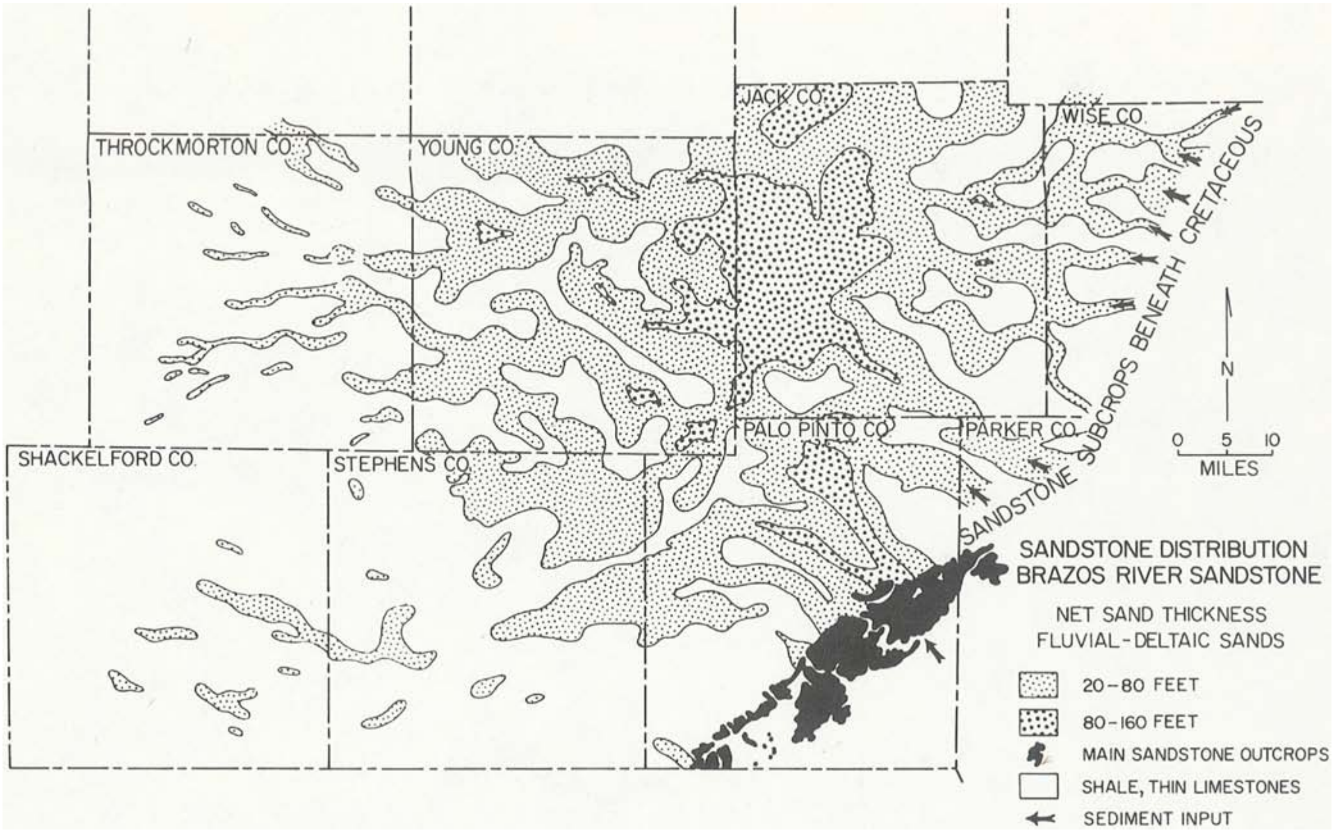

Figure 29. Net-sandstone map, Brazos River Formation, Strawn Group, North-Central Texas. Subsurface control based on approximately 1,300 wells; data on open-file, Texas Bureau of Economic Geology.

Overlying the bay mudstone is the conglomerate and coarse sandstone of the fluvial facies. This upper unit consists of friable sand with small-scale trough cross-beds at the top and indurated, silica-cemented conglomerate at the base; the conglomerate is a chert-arenite. The largest clasts exceed 60 mm in diameter at Locality C and the average maximum size grade in eastern Palo Pinto County falls within the pebble size range. Large-scale troughs are the dominant sedimentary structure in the conglomerate; tabular cross-beds, though present, are not common. Horizontally laminated beds and mud partings are entirely absent. Higher in the facies, the coarser clasts first become restricted to the basal scour zone of individual troughs and are finally lost altogether. The friable sandstone at the top is commonly missing from the section, as it quickly breaks down to form a sandy soil that covers the upper surface of the resistant conglomerate escarpment.

There are two alternative interpretations for explaining the depositional environment of the Brazos River fluvial facies. The first of these requires that the upper part of the formation represent an apron of alluvial fans shed directly from the Ouachita tectonic front to the east; thus the fluvial facies in the Mineral Wells area would be a braided stream complex. Certain aspects of the texture and sedimentary structures in the facies are suggestive of braided streams. The abundance of large-scale troughs, the generally coarse texture of the sediment, and the lack of shale or mudstone all indicate a high-bed-load stream system. On the other hand, it seems improbable that a braided stream complex should be laid down directly on top of a delta.

An alternative interpretation is that the coarse-grained unit is a valley-fill fluvial system. Valley-fill systems develop on alluvial plains as the result of changes in base level. One way of accomplishing this without resorting to worldwide eustatic sea-level changes would be for a fluvial-deltaic system to prograde for a great distance over the shallow shelf and then be abandoned through avulsion to a more efficient, higher-gradient system. The avulsion and consequent readjustment of the fluvial profile of equilibrium would increase the competence of the stream system and result in its incision

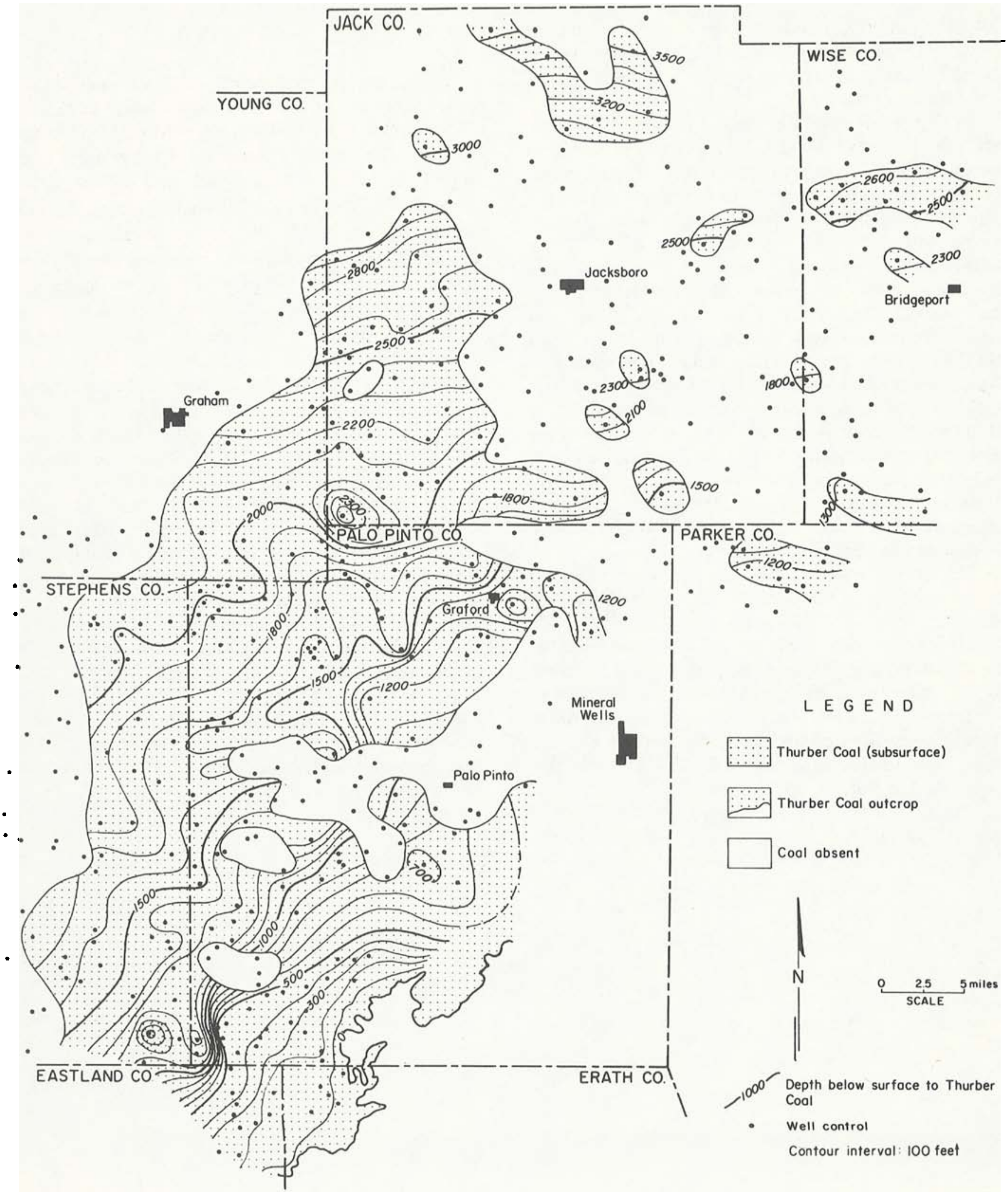

Figure 30. Subsurface distribution of the Thurber Coal, Strawn Group, North-Central Texas. Based on 500 wells. Data on open-file, Texas Bureau of Economic Geology.

into the underlying sediment. Such a system would have confined flow within an incised channel and, therefore, would have the competence to transport very coarse detritus.

In southwestern Palo Pinto County, the deltaic and fluvial facies of the Brazos River Formation grade into a large number of thin, fossiliferous, calcite-cemented sandstone beds that are separated from each other by varying thicknesses of mudstone and shale (see fig. 24). Many of the sandstone beds have been intensively burrowed. The macrofauna is a shallow shelf assemblage of brachiopods and crinoid columnals. These thin sheet sands represent marginal delta-front sands that have been reworked by marine processes and transported along strike to the southwest under the influence of counterclockwise longshore drift. A thin progradational sequence occurs beneath the lowest of the sandstone units. Higher up, however, individual sandstone units have sharp basal contacts with the underlying mudstone. Rapid lateral changes from sandstone to nodular or flaggy limestone are common.

The Brazos River Formation (fig. 29) exhibits a facies tract similar to that of the upper part of the Mingus Formation. The principal deltaic complex for the eight-county area was again centered in Jack and Young Counties. Fluvial feeders supplied sediment to this area from the east and southeast. Farther to the west, the laterally equivalent KMA carbonate-bank complex developed on the Eastern Shelf beyond the influence of Brazos River deltaic progradation (figs. 5, 25, 26).

SUMMARY

The upper Strawn overlies a thick sequence of lower Strawn and Atoka fan deltas and slope depositional systems that constitute the principal fill for the Fort Worth Basin. Beginning with deposition of the Buck Creek and Dobbs Valley Sandstones, fluvial and deltaic units prograded across the basin fill and far westward onto the adjoining Concho Platform. Because the Midland Basin had not yet begun to subside significantly, there was no localized break in slope at which to form a slope depositional system. The Buck Creek and Dobbs Valley deltaic systems constructed a platform on which later Strawn carbonate banks and deltaic systems were deposited adjacent to the slowly deepening Midland Basin. Farther east, high-constructive lobate and elongate deltas built onto the shallow marine shelf behind the carbonate banks. Constructive facies predominate in all of these systems, with destructional facies being limited largely to thin, discontinuous sandy limestone units and to fossiliferous mudstones.

Coals occur in the delta-plain facies of some middle Strawn deltas, but they most commonly have a detrital origin, having been deposited in interdistributary or interdeltaic embayments. Thick delta-plain marsh deposits are absent due to the high structural stability of the shelf that precluded adequate continuous subsidence. The best Strawn coal, the Thurber Coal, does not exceed 36 inches in thickness.

DEPOSITIONAL SYSTEMS IN THE PENNSYLVANIAN CANYON GROUP OF NORTH-CENTRAL TEXAS

A. W. Erxleben[3]

The Canyon Group is a sequence of Upper Pennsylvanian (Missouri Series) carbonate and terrigenous clastic rocks (fig. 31) in North-Central Texas. The rocks dip 0.5 to 1 degree westward into the subsurface. Stratigraphic units include, in ascending order, the Palo Pinto Limestone, Wolf Mountain Shale, Winchell Limestone, Placid Shale, Ranger Limestone, Colony Creek Shale, and Home Creek Limestone.

The area of this report includes 12,000 square miles and comprises all or parts of Palo Pinto, Jack, Wise, Montague, Clay, Wichita, Archer, Young, Stephens, Shackelford, Throckmorton, Baylor, and Wilbarger Counties. The outcrop belt extends through eastern Stephens, northwestern Palo Pinto, southeastern Jack, and into western Wise County, where Pennsylvanian rocks are unconformably overlain by eastward-dipping Cretaceous sediments. Surface mapping and stratigraphic studies have been restricted to northern Palo Pinto, southeastern Jack, and western Wise Counties.

The Canyon Group is a sequence of four thick limestones with interstratified shales and sandstones. The goal of the study was to define terrigenous clastic depositional systems and to relate them to associated carbonate systems. A facies map was constructed and 42 measured sections were described. The Canyon Group was studied in the subsurface using 1,570 electric and sample logs. Refer to Sellards (1932), Girard (1959), and Moore and Brown (1972) for previous studies in the area.

CANYON DEPOSITIONAL SYSTEMS

The Canyon Group in North-Central Texas is composed of several distinctive depositional systems (fig. 32); 1) Perrin delta system; 2) Henrietta fan-delta system; and 3) various carbonate systems (bank systems, shelf systems, platform systems, shelf-edge-reef systems).

Perrin Delta System

Outcropping facies.—The Perrin system (Pollard, 1970), is composed of terrigenous clastic facies within the Wolf Mountain, Placid, and Colony Creek Formations. The Perrin high-constructive delta system prograded northwestward through eastern Jack and western Wise Counties (figs. 33, 34). Constructional deltaic deposition ceased periodically due to: 1) decreased tectonism in the Ouachita folded belt; 2) changing climatic conditions; 3) basinal sea-level changes; 4) shifts to deltaic progradation in other areas; or 5) combinations of these factors. Deltaic abandonment and destruction were marked by marine transgressions and deposition of shelf carbonates.

Distributary-channel-fill sandstones are massive and may cut underlying delta-front sands and muds. Distributary-channel-fill sandstones are normally coarser grained than underlying delta-front facies. Delta-front and distributary-channel facies are unfossiliferous except for feeding trails on upper surfaces. Upper surfaces locally show oscillation, interference, and current-ripple bedforms. Contemporaneous and post-depositional slumping and growth faulting of delta-front and distributary-mouth-bar sandstones is common in Canyon deltaic sequences. Prodelta and distal delta-front facies are well laminated and contain reddish claystone nodules and fine plant debris; they are commonly dark gray to black. Fine-grained distributary-channel and delta-front sandstones are commonly gradational with underlying sandy-silty prodelta mudstones. Deltaic sandstone bodies may be 75 feet thick, but are commonly from 20 to 40 feet thick; they thin laterally and normally interfinger with surrounding mudstones.

The Perrin system contains both lobate and elongate (bar-finger) deltaic facies. Lobate deltas are common in the Wolf Mountain and Placid Formations; elongate, bar-finger sandstones are more common in the Placid Formation. Fine-grained proximal delta-front sandstones of high-constructive lobes are normally massive, highly contorted fine-grained sandstones rich in plant debris. Clay casts and ferruginous claystone nodules are common in massive delta-front and distributary-channel sandstones. Invertebrate fossils are rare in most prodelta mudstones, but mudstones deposited in front of minor distributaries may contain crinoids and mollusks.

An increase in abundance of thin, fine- to very fine-grained sandstone and siltstone beds near the tops of prodelta/distal delta-front facies is characteristic of the coarsening-upward progradational sequence that is common in high-constructive deltas. Thin distal delta-front facies are rich in fine plant debris and may show rippled upper surfaces. A variety of load casts, flute casts, and feeding

[3]Exxon, U.S.A., Houston, Texas

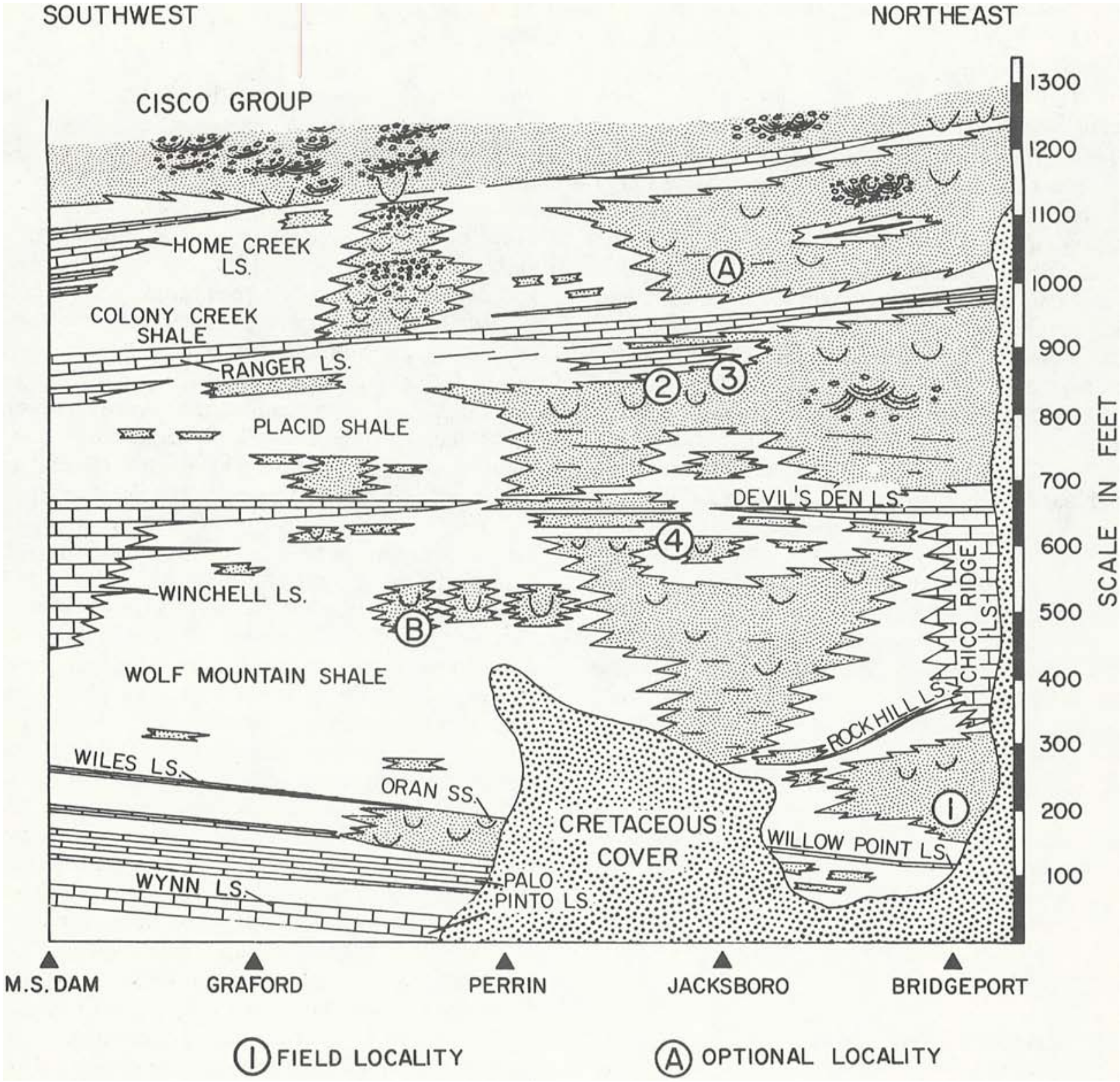

Figure 31. Schematic facies cross section along outcrop, Canyon Group, Jack and Wise Counties, Texas. Based on 40 measured sections.

trails are common on undersurfaces of thin, flaggy sandstone beds. Thin distal delta-front sandstones are commonly graded and may display small-scale trough cross-beds; horizontal laminations, however, are the most common sedimentary structures. Distal delta-front sandstone beds were probably deposited by turbidity currents generated by high discharge. Flood surges cut through distributary-mouth-bar facies, and turbidity currents were generated which redeposited sands on prodelta muds. Thin sandstone beds are characteristically rolled and contorted due to contemporaneous slumping and subsidence into water-saturated prodelta muds. High-constructive elongate deltas such as occur in the Placid Formation, are typified by as much as 100 feet of highly contorted, superposed channel-mouth-bar and distributary-channel sandstones.

Delta-plain deposits are rare in outcropping Canyon Group sediments. Even though deltaic sandstones are commonly rich in carbonaceous plant debris, lignitic clays and coals are rare. A possible explanation is that these uppermost deltaic sediments were thin and were commonly destroyed by marine processes after deltaic abandonment. Subsidence was slow on the tectonically

Figure 32. Depositional systems of the Canyon Group, North-Central Texas.

stable Eastern Shelf, and marine waves, currents, and organisms had ample opportunity to rework and destroy the thin organic deposits. More commonly than not, reworked sandstones and fossiliferous shelf mudstones rest directly on abandoned distributary and delta-front facies. Limestones, such as the Winchell, Ranger, and Home Creek, transgressed the abandoned delta platform.

In the Placid and Colony Creek Formations, coarse-grained channel-fill fluvial sandstones and chert-pebble conglomerates cut underlying fine-grained deltaic sandstones and mudstones. These coarse-grained facies contain medium- to large-scale trough cross-beds. Individual fluvial bodies are 10 to 20 feet thick. The coarse-grained facies may represent a variety of braided, coarse-grained meanderbelt facies, or, perhaps, confined valley-fill fluvial deposits.

The Colony Creek interval of the Perrin delta system east of Jacksboro is locally overlain by 3 to 4 feet of heavily burrowed calcareous sandstone and limestone that is riddled with straight and branching, vertical and horizontal burrows up to 1 inch in diameter. The burrowed zone is overlain by 10 to 20 feet of highly fossiliferous mudstone, which is capped by the transgressive Home Creek shelf carbonate. The highly bioturbated calcareous sandstone unit is a relatively widespread sheet of destructional-deltaic sandstone developed on the abandoned Perrin delta system.

Subsurface distribution.—A net-sandstone map of the Wolf Mountain interval of the Perrin delta system (fig. 35) shows a complex of dip-oriented, linear and bifurcating deltaic lobes. Progradational delta lobes can be recognized in the subsurface by distinctive E-log patterns (fig. 36). These trends extend westward and northwestward for 80 miles across the Eastern Shelf. The maximum sandstone thickness in the Perrin delta system occurs just south of the town of Jacksboro, only 5 to 10 miles downdip from outcropping deltaic sandstones. A series of linear trends extends northwestward from the outcropping Perrin delta system; in western Jack County, these linear trends shift westward and continue across Young and southern Archer Counties and into Throckmorton and Baylor Counties. This shift in sandstone trend may be due to the influence of the Winchell carbonate bank system, which had slight depositional relief southwest of the Perrin system. Principal sandstone trends are separated by interdistributary and interdeltaic-embayment areas.

Deposition in the Wolf Mountain interval of the Perrin delta system was in part contemporaneous with deposition of adjacent carbonate banks. Thick carbonate bank systems were present to the southwest (Winchell System) and to the northeast (Chico Ridge System). The banks originated as algal-crinoid mounds (fig. 36) growing atop abandoned deltaic and interdeltaic sediments of the lower Wolf Mountain interval. Deltaic lobes of the Perrin delta system prograded across the Eastern Shelf between these shoal-water banks (fig. 35). Outcropping carbonates exhibit numerous depositional breaks up to 3 feet thick composed of terrigenous silty and sandy clay which record periods of local detrital influx from the prograding Perrin delta system. Intertongued deltaic sediments probably represent discrete, relatively short time periods as compared with slowly accumulating algal carbonates. Phylloid algae and crinoids grew and acted as baffles for lime mud, but occasional shifts in prograding deltaic lobes introduced fine clastic debris which locally destroyed the carbonate-producing and -trapping organisms, causing slight shifts in carbonate deposition to new, less turbid sites.

Depositional relief on the Winchell and Chico Ridge carbonate banks influenced the path of prograding Perrin delta lobes (fig. 35). Deltaic lobes were deflected around the carbonate banks. Toward the end of Wolf Mountain deltaic deposi-

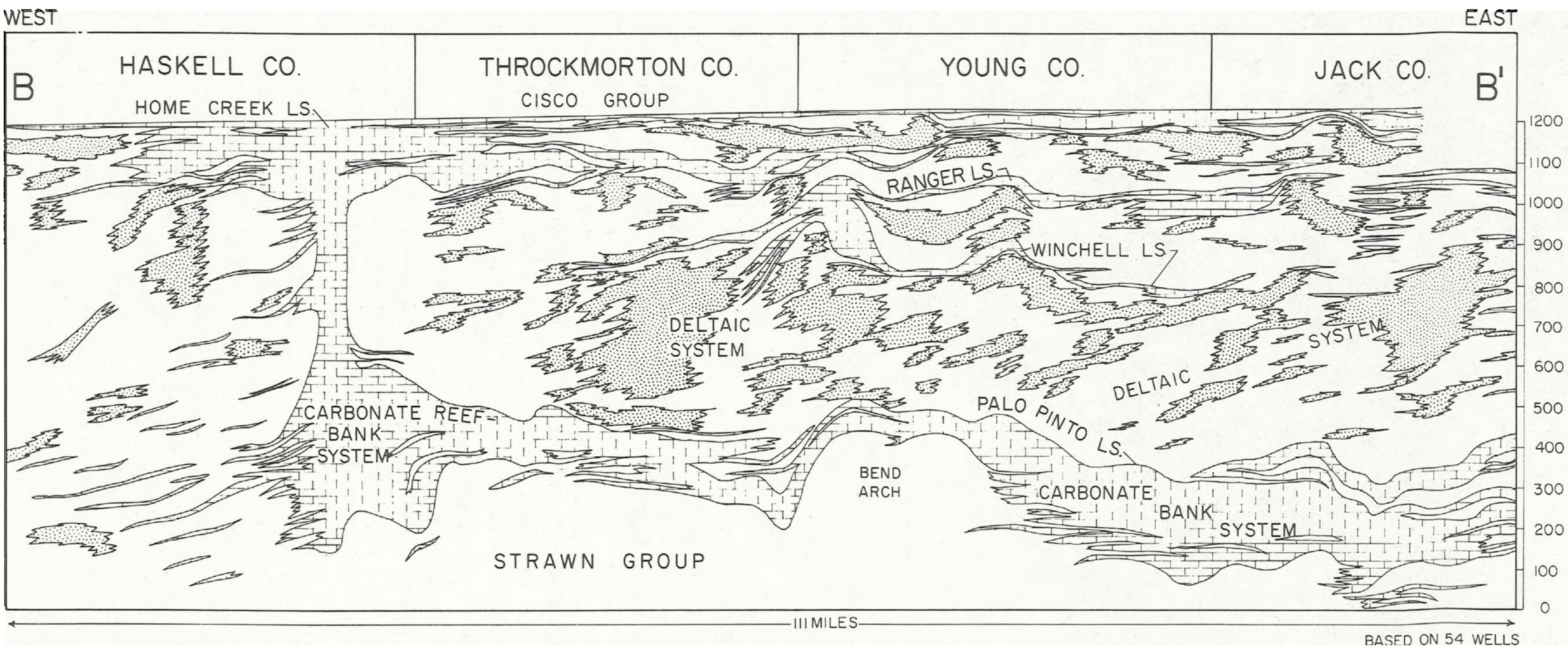

Figure 33. Subsurface cross section B-B′ (dip) from Haskell to Jack Counties, Texas, showing facies of the Canyon Group. Based on 54 wells. See fig. 4 for line of section. Data on open-file, Texas Bureau of Economic Geology.

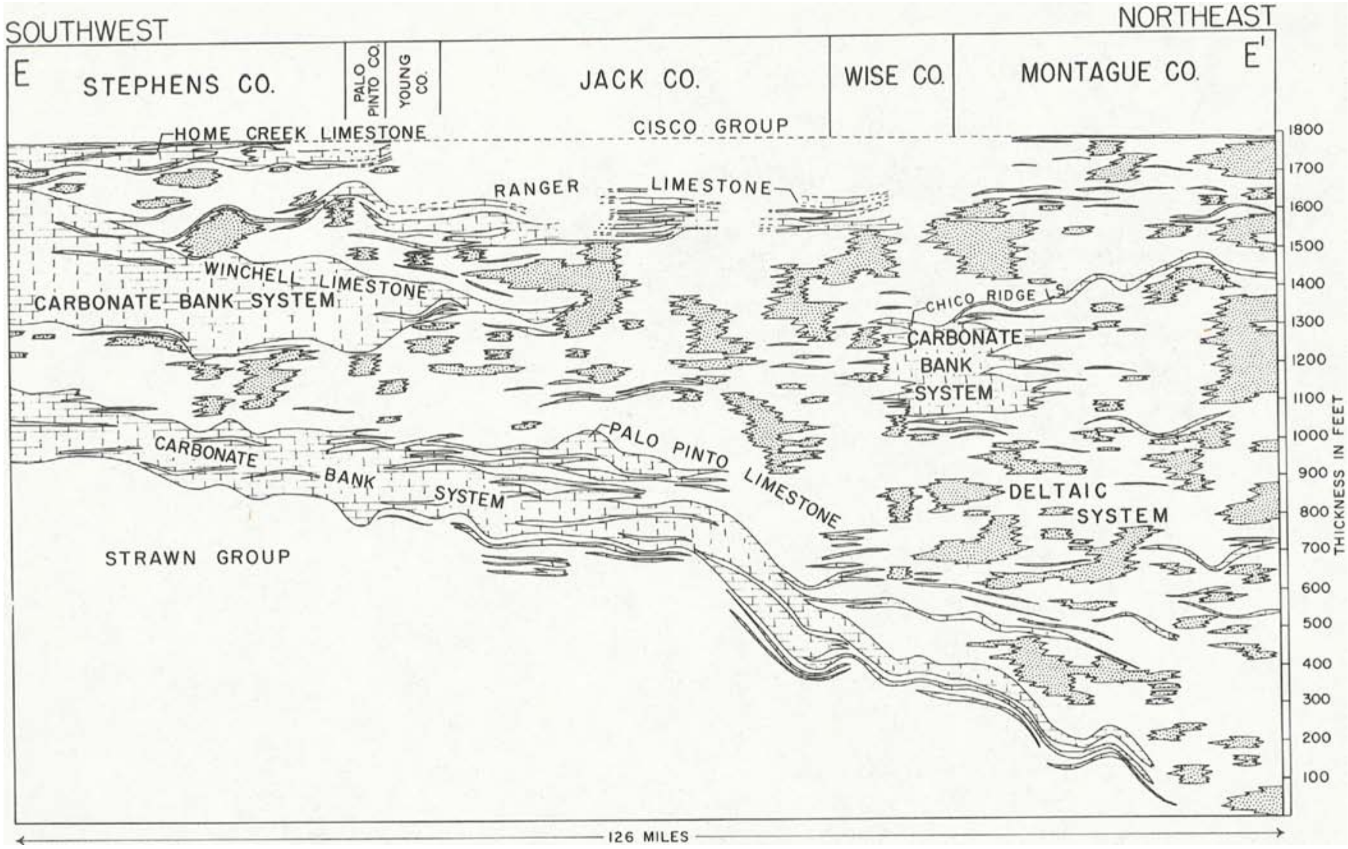

Figure 34. Shallow subsurface cross section E-E′ (strike) from Stephens to Montague Counties, Texas, showing facies of the Canyon Group. Based on 48 wells. See fig. 4 for line of section. Data on open-file, Texas Bureau of Economic Geology.

tion, the carbonate banks may have had little, if any, depositional relief compared to the surrounding deltaic platform.

With general abandonment and subsidence of the Perrin delta system, Winchell and Devil's Den algal carbonates spread out from the old carbonate-bank systems and onlapped the edges of foundering deltaic lobes.

During deposition of the Placid Formation, lobes of the outcropping Perrin delta system (fig. 37) again prograded northwestward and westward in a series of linear and branching trends across northern Jack, northwestern Wise, and southern Clay and Montague Counties. Thick subsurface sandstones north of Wizard Wells tie with outcropping Perrin deltaic sandstone complexes, including the massive, contorted bar-finger sandstones of the outcrop. These thick deltaic lobes prograded 30 miles downdip from outcrop across the northern part of the stable Eastern Shelf. Two thinner deltaic lobes extend westward from outcrops south of Wizard Wells, and a smaller system of lobes extends a short way downdip in southern Jack and northern Palo Pinto Counties.

A relatively large bifurcating lobe prograded basinward across the Eastern Shelf through northern Stephens and southern Young Counties. Outcropping sandstones of this lobe should be found in northwestern Palo Pinto County, around the shores of Lake Possum Kingdom. Deltas prograded southward into Texas from Oklahoma during the Placid interval.

In western Stephens and southeastern Shackelford Counties, the Placid interval is represented by massive carbonate units (fig. 36) of the combined Winchell and Ranger Limestones. As deltaic progradation ceased in the northeast, transgressive shelf carbonates of the Ranger Limestone spread out and covered the abandoned and subsiding deltaic lobes.

The Ranger Limestone (fig. 38) is composed of the carbonate bank system in Stephens and Shackelford Counties and of the irregular, blanket-like transgressive shelf carbonates that overlap the Perrin delta in Jack and Clay Counties.

Perrin delta model.—An idealized sequence of Perrin delta progradation and abandonment includes constructional and destructional phases (fig.

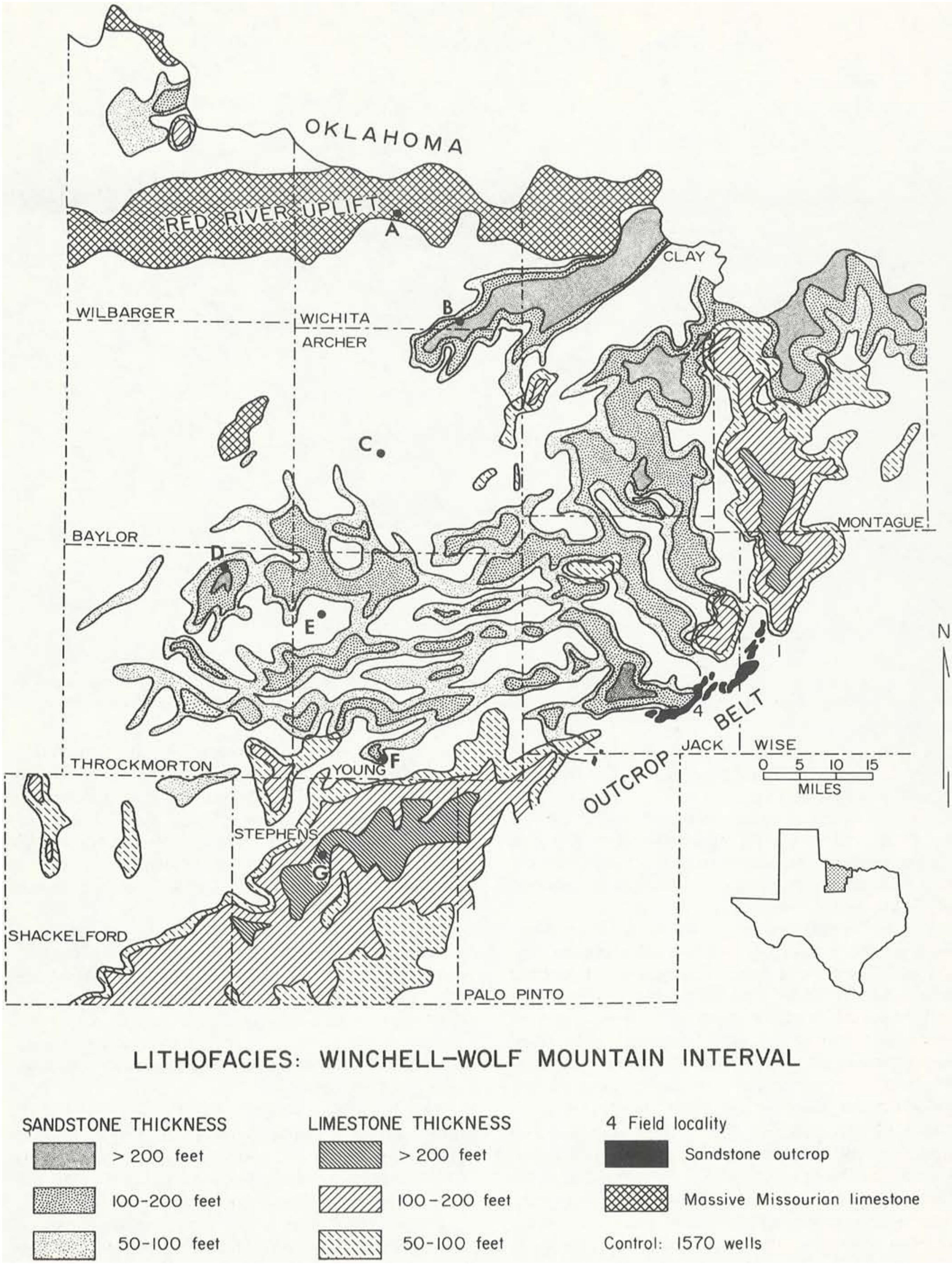

Figure 35. Net-sandstone and -limestone map of the Winchell-Wolf Mountain Formations, Canyon Group, North-Central Texas. Letters (A-F) refer to typical E-log patterns, fig. 36. Area without pattern is shale or less than 50 feet of sandstone or limestone. Based on 1,570 wells; data on open-file, Texas Bureau of Economic Geology.

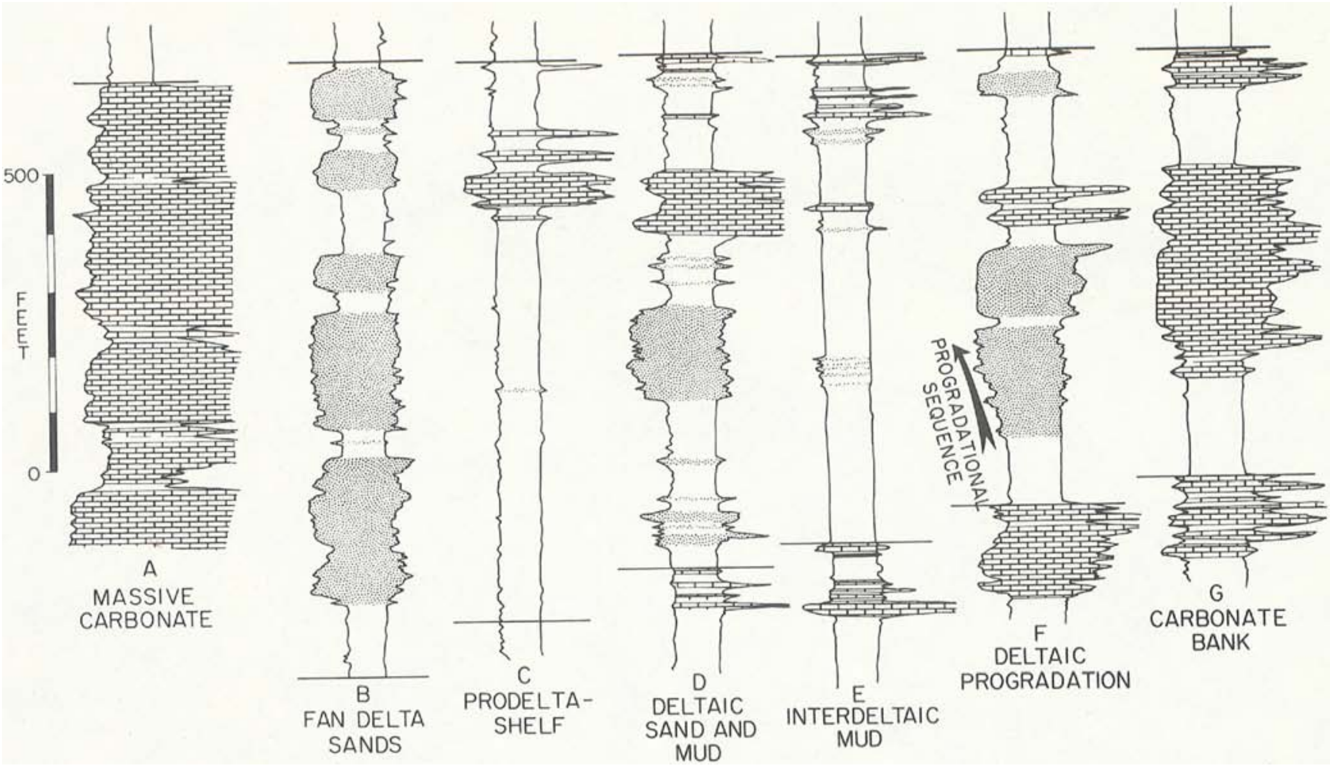

Figure 36. Typical E-log patterns of facies within Canyon depositional systems, North-Central Texas. See fig. 35 for location of E-logs.

39). The constructional sequence, in ascending order, includes: 1) laminated, largely unfossiliferous, prodelta mudstones, containing abundant fine organic debris and ferruginous claystone nodules; 2) thin-bedded, graded, commonly rolled and contorted, distal delta-front fine-grained sandstones and siltstones in laminated shale; 3) fine-grained, more massive proximal delta-front sandstones, which may be heavily contorted and contemporaneously faulted, and which contain abundant plant debris; 4) massive, fine- to medium-grained distributary-channel sandstones which contain large scour-and-fill structures and local clay-chip conglomerates along with abundant plant stems and leaves; and 5) thin, often lignitic to coaly, delta-plain, sandy, silty mudstones, which commonly appear homogeneous and may be cut by symmetrical tidal channels. Destructional facies atop abandoned deltaic sequences generally include: 1) highly burrowed, fine-grained destructional sandstones up to 6 feet thick, which may contain *Myalina* shells; 2) fossiliferous silty mudstones, which have been heavily bioturbated; 3) highly fossiliferous open-shelf mudstones with abundant brachiopods, gastropods, sponges, crinoids, corals, and other invertebrates; and 4) phylloid algal-crinoid shelf carbonates.

The Perrin delta-facies relationships suggest affinities with Holocene lobate and elongate, high-constructive deltas of the Mississippi complex. Donaldson and others (1970), studying the Holocene Guadalupe delta at the head of San Antonio Bay, Texas, reported a facies framework similar to that of the lobate and elongate Mississippi delta complex. The Guadalupe delta, however, is prograding into a shallow bay under more stable tectonic conditions. Donaldson and others suggest that this accounts for the slight overlap of Guadalupe subdeltas and for the relatively thin prodelta sequences. Subsidence on the Guadalupe delta is due to compaction of thin prodelta and estuarine muds, as compared to the Mississippi system where the basinal subsidence is high and prodelta muds are thick. The tectonic stability of San Antonio Bay is much like the structural conditions that prevailed on the Pennsylvanian Eastern Shelf.

Henrietta Fan-Delta System

The Henrietta fan-delta system is a thick system of coarse clastic wedges in northern Montague, Clay, eastern Wichita, northern Archer, and eastern Baylor Counties, which built southward into Texas during Canyon deposition (fig. 32).

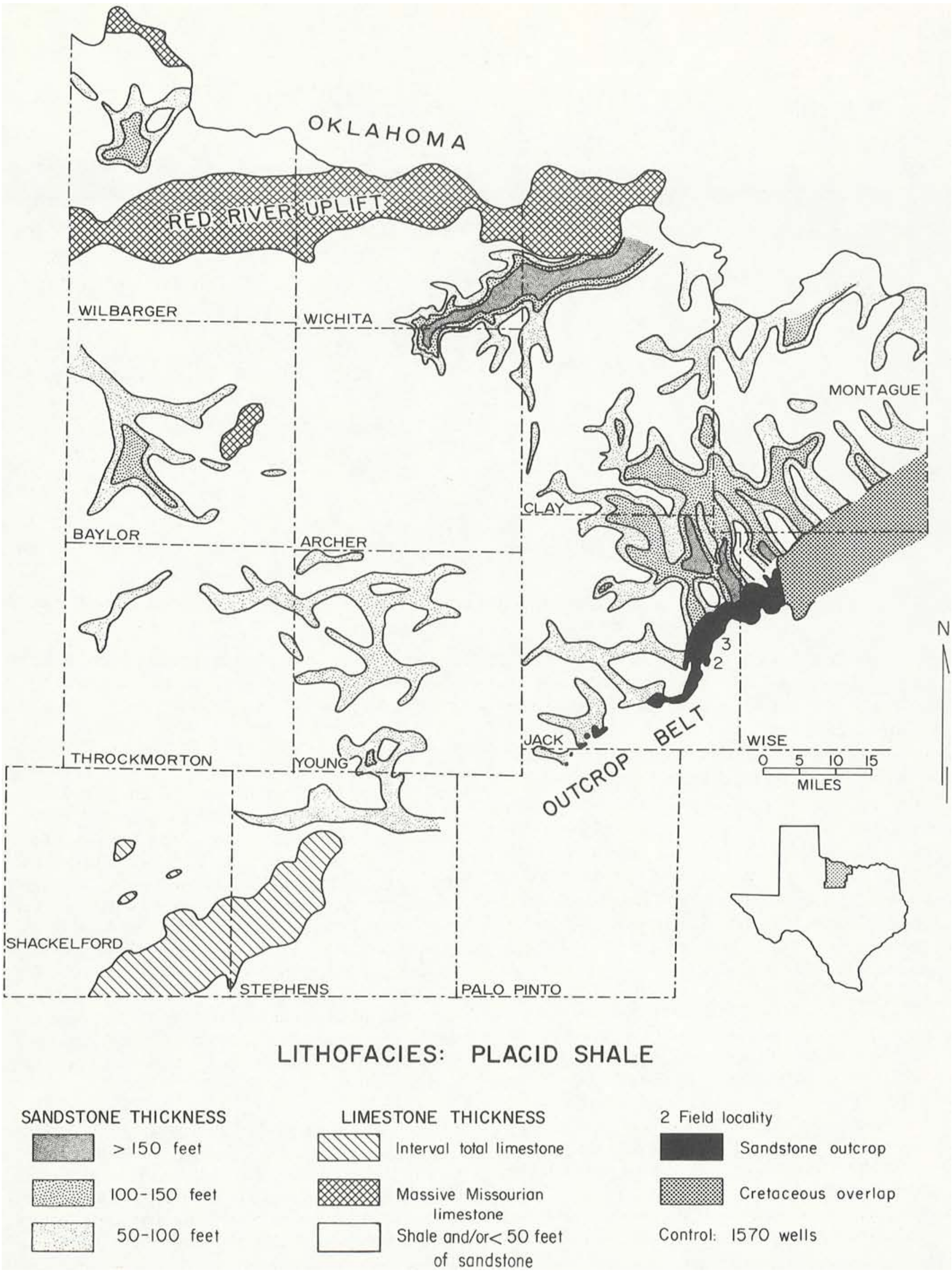

Figure 37. Net-sandstone and -limestone map of the Placid Shale, Canyon Group, North-Central Texas. Area without pattern is shale or less than 50 feet of sandstone or limestone. Based on 1,570 wells; data on open-file, Texas Bureau of Economic Geology.

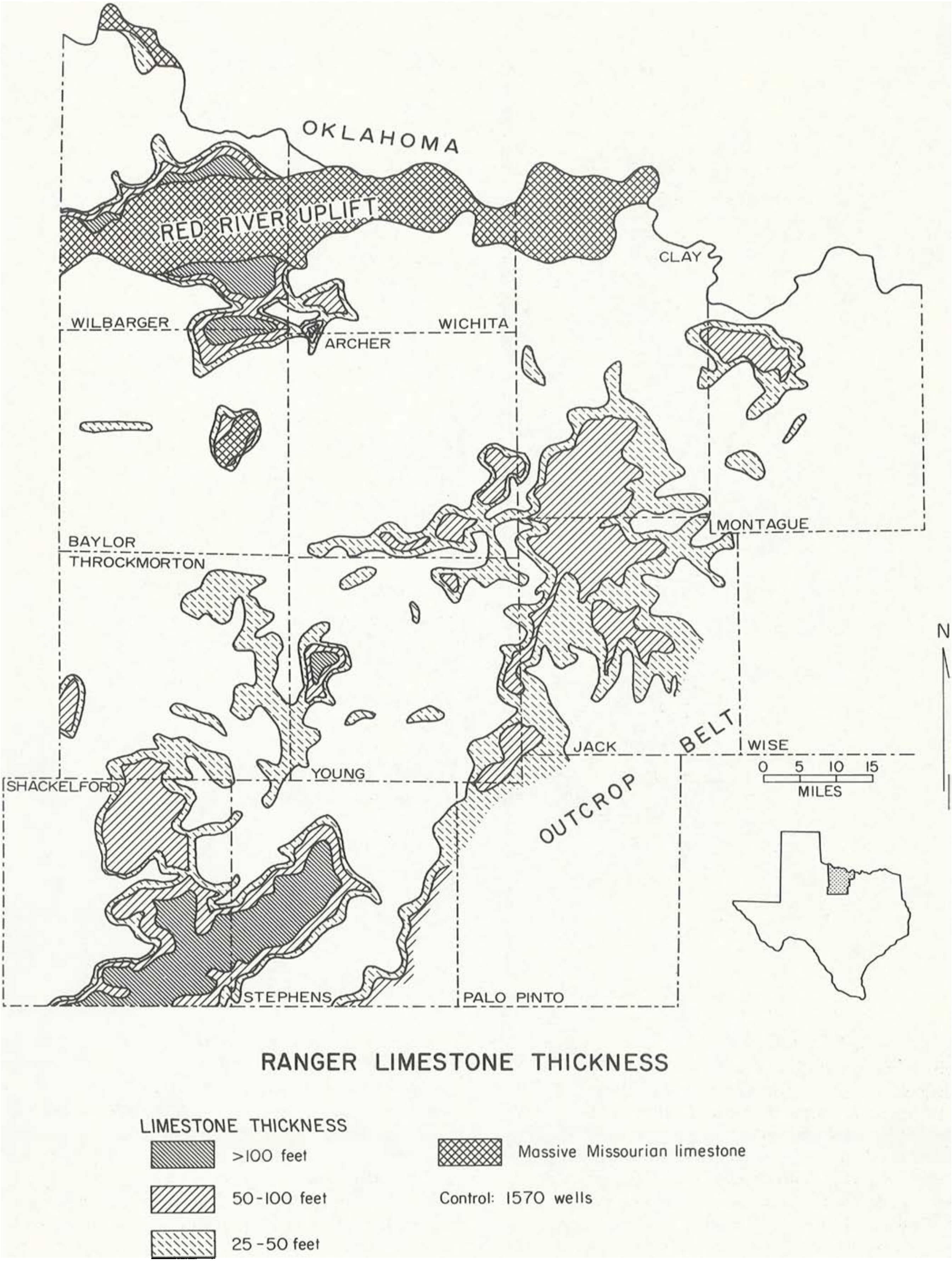

Figure 38. Isopach map of Ranger Limestone, Canyon Group, North-Central Texas. Area without pattern is shale or sandstone or less than 25 feet of limestone. Based on 1,570 wells; data on open-file, Texas Bureau of Economic Geology.

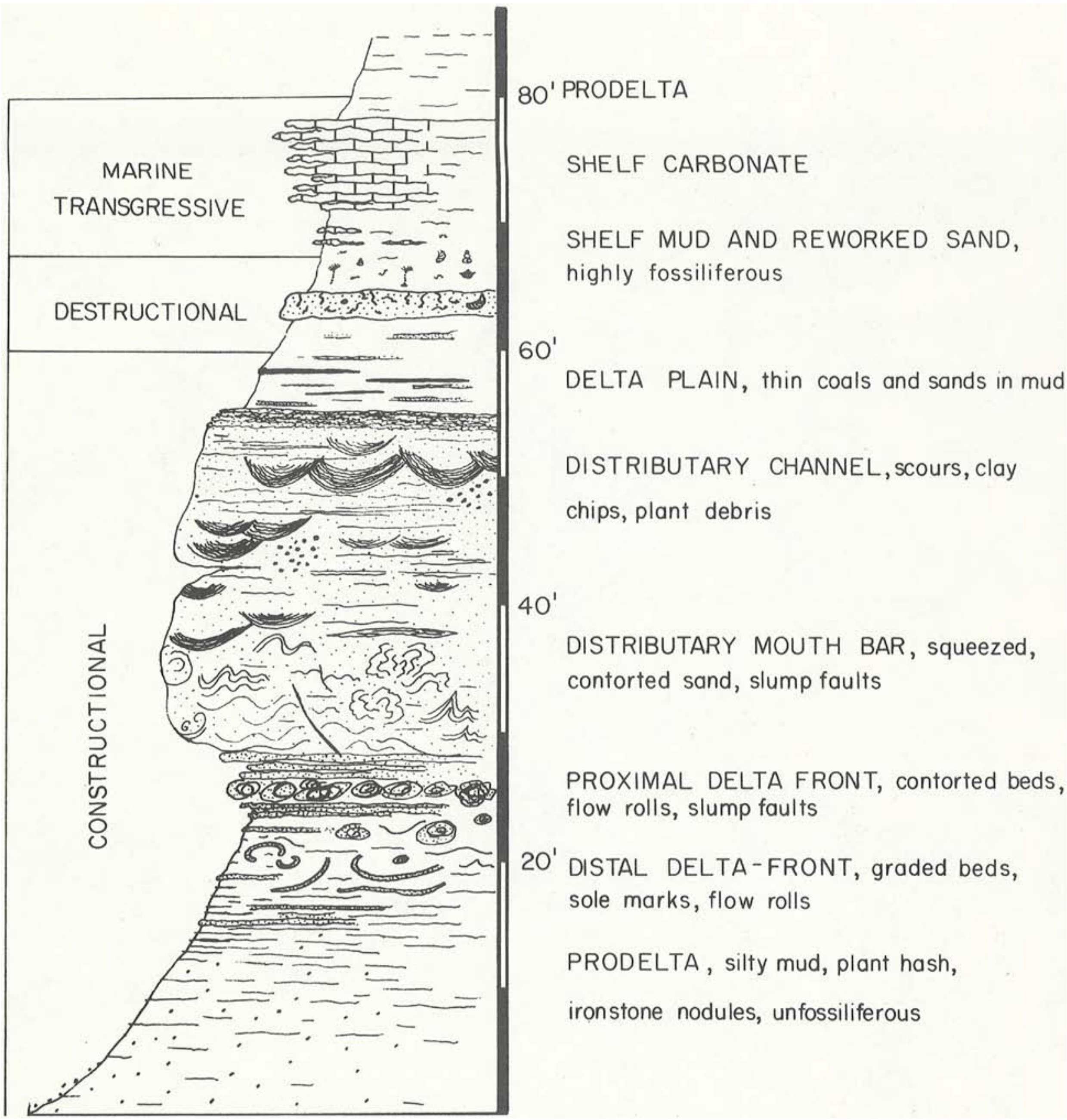

Figure 39. Idealized delta sequence, Canyon Group, North-Central Texas.

A fan delta (Holmes, 1965) is an alluvial fan which progrades into a body of water from a closely adjacent highland (McGowen, 1970). Although modern terrestrial alluvial fans have received much attention by workers such as Blissenbach (1954), Beaty (1963), Bull (1963), Denny (1964), Hooke (1967), and others, modern fan deltas have received relatively little study. McGowen (1970) presented a study of processes and facies of an active fan delta in Nueces Bay, Texas. Kidson (1953) described a flood on the Lynmouth fan delta which transported boulders up to 20 feet in diameter and deposited 50,000 cubic yards of sediment on the delta in 24 hours.

Fan deltas, like alluvial fans, have relatively small drainage areas and flash-flood discharge. Sedimentation is through the activity of relatively high-gradient braided streams. The percentage of coarse- to fine-grained sediments is higher than in high-constructive lobate and elongate deltas. Fan-delta wedges are characterized by thin prodelta facies. The braided fluvial system extends to the toe of the delta, and distributaries are generally short and braided. The system carries a high bed load which it can transport only during peak discharge; sediments become finer toward the toe of the fan delta. Fan deltas, like alluvial fans, may contain arkosic sands, gravels, and various rock fragments. The Henrietta fan-delta system is entirely within the subsurface; therefore, outcropping facies are not available for study.

Subsurface distribution.—The net-sandstone map of the Wolf Mountain interval (fig. 35) reveals the presence of thick sandstones in northern Montague, northern and eastern Clay, southeastern Wichita, and northeastern Archer Counties, which extend into the area from southern Oklahoma. The fan-delta system in Montague County (fig. 34) prograded southward while two massive lobes of northern Clay County accreted southwestward. The stacked nature of these massive clastic lobes (fig. 36) is readily apparent from the contour patterns. In northern Clay County, within the Wolf Mountain interval, sandstones locally thicken from 25 to 500 feet in less than 3 miles.

The largest lobe of the Henrietta System prograded southwestward through northern Clay and into Wichita and Archer Counties during deposition of the Wolf Mountain interval. The system bifurcated, sending smaller sublobes off southward (fig. 35). A thick lobe in eastern Clay County has a well-defined, narrow feeder trend which extends southwestward from the northwest corner of Montague County, while southeast of Henrietta, the system fans out into a broad lobe. Lobes of the Perrin delta system intertongue with extended lobes of the Henrietta fan-delta system in south-central Clay County. Sandstone trends indicate that sediments prograded into this area from sources both in the Ouachita fold belt and in the mountains of southern Oklahoma.

Development of the Henrietta system continued during the Placid interval (fig. 37); small lobes continued to stack up in northern (fig. 36) Montague County. The lobe in northeastern Clay County maintained its position but was greatly reduced in size. The major lobe of northern Clay, southeastern Wichita, and northeastern Archer Counties showed little additional progradation during Placid deposition.

During deposition of the Colony Creek interval, small lobes persisted in northern Montague and northeastern Clay Counties. The principal lobe prograded 50 miles farther across the shelf, and was deflected around a reef-bank system in west-central Baylor County. Several lobes developed in Baylor County, some of which extended southward into northern Throckmorton County. Major lobes (up to 435 feet) stacked up in northwestern and north-central Archer County as the system was rejuvenated by late Missouri Arbuckle orogeny.

North of the Red River uplift, in northern Wilbarger County, fan deltas built southwestward during Canyon deposition, and lobes reached thicknesses of 100 to 150 feet in each of the Canyon intervals. Henrietta fan deltas are thick, massive, coarse-grained facies, commonly with sharp erosional bases and tops; progradational sequences are rare. The fans are commonly arkosic ("granite wash") and poorly sorted.

Henrietta fan-delta model.—As the Arbuckle and Wichita Mountain ranges were uplifted during the two basic phases of the Arbuckle orogeny (late Desmoines and late Missouri through Virgil), thick, high-gradient fan-delta aprons of coarse arkosic clastics were shed both to the north and to the south. The southward advancing systems filled the relatively shallow Ardmore and Marietta Basins, and in Missouri (Canyon) time prograded into North-Central Texas (fig. 32).

The area immediately south of the Muenster Arch-Red River uplift system was an unstable trough (northern remnant of the old Fort Worth Basin) during Missouri deposition. As sediments of the Henrietta system were deposited, the trough subsided, allowing fan-delta wedges to stack up to great thicknesses.

The Perrin high-constructive delta system (fig. 40) prograded over a tectonically stable shelf composed of thick subjacent Desmoines sediments. Subsidence was slow and deltaic sediments did not aggrade to great thicknesses; rather, they rapidly prograded basinward as a series of relatively thin, shifting lobes. The Perrin delta system was fed by low-gradient fluvial systems which crossed a broad coastal plain just east of the Ouachita Mountains. The Henrietta fan-delta system (fig. 40), on the other hand, was fed by high-gradient (as evidenced by the coarse, poorly sorted load), probably braided streams, which crossed a relatively narrow coastal plain consisting of stacked alluvial fans. The path of fan-delta progradation was probably controlled by structural weakness and subsidence south of the Red River uplift (Wermund and Jenkins, 1969).

Burke (1967) described two fan deltas that are currently prograding into the subsiding Yallahs Basin of Jamaica from the Port Royal and Yallahs Mountains. The two fan deltas have built large submarine fans which extend to the basin floor.

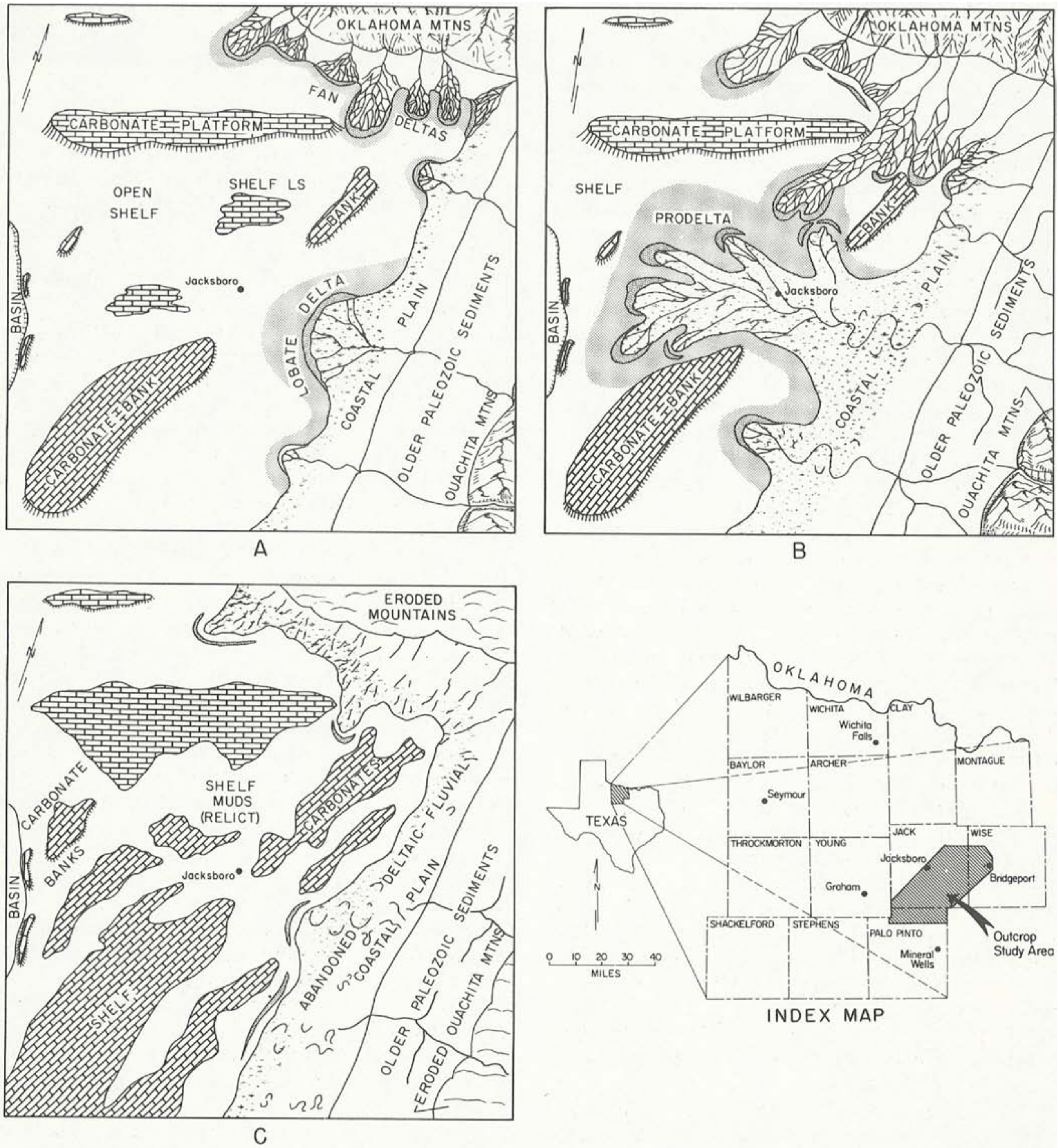

Figure 40. Evolution of Canyon paleogeography. A. Early progradation of delta systems. B. Maximum extent of delta development. C. Shelf transgression over abandoned deltaic facies. Based on three Canyon delta cycles.

Gradients both on the subaerial and subaqueous fans are high, and sediments include fragments of andesite and granodiorite. The Henrietta fan-delta system of the Canyon Group bears many similarities to the Yallahs Basin model. Thick wedges of coarse arkosic clastic sediments stacked up in the subsiding northern remnant of the Fort Worth Basin, fed by sources in the Arbuckle-Wichita Mountains to the north. A rather large carbonate platform (Red River carbonate platform) lay just to the west and north of the prograding fan system (fig. 32). The Henrietta system must have prograded into a relatively shallow, yet subsiding trough. Rates of subsidence in the northern Fort Worth Basin approximately kept pace with or lagged slightly behind clastic sediment input, allowing subaerial exposure and formation of thin coals.

Carbonate Systems

Outcropping Canyon Group carbonates are irregularly and unevenly bedded, well-indurated phylloid algal biomicrudites, with local sparry zones. Zones and lenses of spar-cemented skeletal lime sand are common, as are thin intraclast-rich beds. Marine invertebrate fossils are common to abundant. Oolites are uncommon, but local zones do exist. Biolithites are uncommon but exist locally as thin buildups. Fusulinid-rich zones are relatively common.

Carbonate systems (fig. 32) comprise 1) algal-crinoid banks of high depositional relief, 2) transgressive shelf carbonates, 3) tectonically stable carbonate-platform systems, and 4) shelf-edge reef-bank systems.

Carbonate-bank systems.—Algal-crinoid carbonate banks existed in the Canyon Group at various times and in various places in the Palo Pinto, Winchell, Ranger, and Home Creek intervals (fig. 32). A carbonate bank is defined as a skeletal limestone deposit that stood above the surrounding sea floor with depositional relief. Banks, unlike reefs, are constructed by nonframework-building organisms, such as marine plants, bryozoa, and crinoids, which produce, baffle, and trap fine lime mud and skeletal debris, thus building up depositionally high areas. Carbonate-bank sequences may contain local biohermal buildups of corals or bryozoa but, for the most part, they appear as biostromes that interfinger with surrounding sediments.

Carbonate banks of the Canyon Group (fig. 32) formed on rather low-energy shallow-shelf areas atop older deltaic sands and muds. Algal carbonate banks probably built up in waters which did not exceed 10 to 15 feet in depth, based on comparisons with recent algal carbonates. Canyon banks tend to be elongate carbonate biostromes which are oriented essentially parallel to depositional strike (northeast-southwest). Thicknesses may reach 100 to 300 feet of massive micritic limestone. Outer shelf carbonate buildups in the Canyon Group commonly are up to 1,300 feet thick. Some carbonate banks may have been emergent at times as evidenced by angular, at least partially pre-lithified, fossiliferous micrite clasts incorporated in flanking talus deposits (i.e., Rock Hill Limestone). Once formed, a carbonate bank influenced the position of later forming banks by offering a high, stable, slowly compacting foundation upon which to build. Carbonate banks (fig. 34), notably the Chico Ridge bank, also formed atop abandoned deltaic platforms.

Transgressive shelf-carbonate systems.—With abandonment of the three major phases of Perrin delta and Henrietta fan-delta progradation, blanketlike shelf carbonates of the Winchell, Ranger, and Home Creek intervals (fig. 40) onlapped the subsiding deltaic lobes. Outcrop studies reveal that phylloid algal biomicrudites predominate, with local concentrations of sparites and intraclast-rich zones (indicative of higher energy conditions) distributed throughout. The blanketlike shelf carbonates are generally 5 to 50 feet thick in outcrop and are irregularly and unevenly bedded. Individual beds average less than one foot in thickness and are separated by thin argillaceous zones introduced from minor deltaic lobes which co-existed to the east.

Thin transgressive shelf carbonates of the Winchell interval extended outward from old carbonate bank areas (fig. 35) after abandonment of the Perrin delta system; local deposits averaging 50 to 60 feet thick are distributed over the Perrin delta of the Wolf Mountain interval in northern Palo Pinto, Jack, Young, and Throckmorton Counties.

A blanket of Ranger Limestone (fig. 38) averaging 40 to 50 feet thick, spread over the Perrin delta system of the Placid interval in Jack and southern Clay Counties. Limestone is generally thicker in interdeltaic areas between the depositionally high deltaic lobes. Carbonates began to accumulate in low interdeltaic areas first, and as deltaic subsidence progressed, they onlapped the surrounding thick deltaic lobes. Shelf carbonates of the Home Creek Limestone are also thicker in interdeltaic and open-shelf areas. Limestones are thin over most of the depositionally high Perrin delta lobes of the Colony Creek interval. Carbonate thicknesses of 20 to 40 feet in those areas are primarily concentrated in interdeltaic areas and over the fringes of delta lobes. Due to the low compactibility of the framework sands, deltaic lobes probably remained as topographically high areas on the sea floor for relatively long periods of time after their abandonment.

Carbonate-platform systems.—During deposition of the Canyon Group, the Red River uplift stood as an east-west-trending series of granitic knobs that supported a massive carbonate system across northern Clay, Wichita, and central Wilbarger Counties (figs. 32, 40). Wells through the carbonate platform indicate that alternating massive limestone and shale sequences commonly reach thicknesses of 2,000 to 3,000 feet in valleys between granitic highs. Some wells penetrate granite at relatively shallow depths, and carbonates in these areas often are only a few hundred feet thick.

The Red River uplift area was a stable platform for carbonate deposition throughout most of Paleozoic time. Clastic sediments of the Strawn and Canyon Groups interfinger with carbonates of the Red River carbonate-platform system along the southern flank of the uplift. Carbonate deposition probably continued near sea level throughout deposition of the Canyon Group, as slow subsidence kept pace with accumulation.

Shelf-edge reef-bank systems.—A lithofacies map for the Missouri Series, prepared by Wermund and Jenkins (1969), shows a series of these massive carbonate bodies along a northeast-southwest trend through eastern Haskell, eastern Jones, western Taylor, southeastern Nolan, northeastern Coke, and northwestern Runnels Counties. Basinward of this line of carbonate buildups the Canyon Group thins rapidly and consists mostly of shale with thin, relatively steeply dipping, limestone stringers (fig. 33). Massive carbonate buildups (fig. 36) are interpreted to be a shelf-edge system of banks and local reefs, which persisted throughout deposition of deltaic and shelf carbonate systems to the east (figs. 32, 40). Some of these carbonate buildups started forming during late Desmoines deposition (upper Strawn Group) and persisted throughout Missouri deposition. Local thicknesses of up to 1,500 feet are not uncommon. Buildups are quite precipitous, with net-limestone values commonly increasing from a few feet to more than 1,200 feet, over horizontal distances of 1 to 2 miles between wells.

The Canyon Group reef-bank system probably began to grow as a complex of late Desmoines and early Missouri algal and crinoid banks on a poorly developed shelf edge, where the slope break was minor. With time, the Midland Basin continued to subside as the Eastern Shelf developed. As the shelf-edge break in slope became more pronounced, carbonate growth was stimulated by the upwelling, cold, calcium-carbonate-charged waters from the deepening basin. Algal, crinoid, and other associated skeletal debris built up at rapid rates in the clear, circulating waters of the outer shelf. Carbonate deposition may have persisted approximately at wave base, and thus rigid-frame-building organisms were not required for the banks to remain as stable depositional highs.

Canyon Group shelf-edge reef-bank systems acted as partial sediment dams for outbuilding slope systems. By the end of the Canyon Group deposition, the Eastern Shelf edge showed a well-developed break in slope, largely due to the stabilizing effects of the massive reef-bank systems. Virgil (Cisco Group) clastic systems prograded to the edge of this well-defined shelf edge and spilled over in a series of thick slope wedges (Galloway and Brown, 1972). With continued Cisco Group clastic influx, the Eastern Shelf built basinward in a series of onlapping and offlapping sequences of clastics and carbonates.

SUMMARY

Mountainous areas included the Ouachita folded belt to the east and the high Arbuckle and Wichita ranges of southern Oklahoma (fig. 40). A broad stable shelf dipped gently to the west toward the Midland Basin, except for local tectonically unstable areas south of the Red River uplift such as the Muenster Arch; the uplift was a stable high which supported a massive carbonate platform. Algal-crinoid banks thrived on the shallow shelf. Outer shelf/shelf-edge reef-bank systems lined the edge of the Midland Basin. The high-constructive lobate and elongate Perrin delta system prograded westward across the shelf (fig. 40A), while thick arkosic Henrietta fan deltas prograded to the south and southwest from the mountains of southern Oklahoma.

With continued progradation of individual deltaic lobes, high-constructive deltas and fan deltas reached far out onto the stable shelf between carbonate banks (fig. 40B). With deltaic abandonment, shelf carbonates spread out from the old carbonate banks and from outer shelf areas and onlapped compacting deltaic sands and muds (fig. 40C). This same basic process of deltaic outbuilding, abandonment, compaction, and carbonate onlap occurred three times, giving the cyclical sequence of deltaic-clastic and shelf-carbonate rocks of the Canyon Group.

CISCO DEPOSITIONAL SYSTEMS IN NORTH-CENTRAL TEXAS

L. F. Brown, Jr.

INTRODUCTION

The Cisco Group (Virgil and Wolfcamp Series) in North-Central Texas is composed of mixed terrigenous clastic and carbonate depositional systems (fig. 41). These sequences crop out along a northeast-southwest trend in the Brazos River Valley (fig. 4). The strata strike N 21° E and dip westward at about 50 feet per mile from Eastland County to central Young County where strike changes to N 61° E with north-northwest dip less than 50 feet per mile. Outcrop is essentially parallel to depositional strike, except in eastern Young, Jack, and Montague Counties where the shift in strike causes the outcrop to trend essentially parallel to paleoslope.

A basinward progression of facies includes the Cisco fluvial-deltaic, Sylvester shelf-edge bank, Sweetwater slope, and Midland Basin depositional systems (fig. 42). The unusual preservation of this extensive facies tract provides the opportunity to examine a principal part of the Virgil and Wolfcamp sediment dispersal system. Fluvial, deltaic, and upslope-shelf facies (1,200 feet thick) can be studied in outcrop; principal shelf-edge bank, slope, and basinal facies (2,500 feet thick) occur exclusively within the subsurface (fig. 5; pl. I). This report is based principally on studies by Brown (1959; 1960a, b; 1962; 1969a, b, c, d); Brown and others (1969); Galloway and Brown (1972, 1973); Brown and Goodson (1972); McGowen (1964); Waller (1966); Ray (1968); Seals (1965); Erxleben (in progress); and Cleaves (in progress). The reader is referred to the introduction for general references to studies in the region.

Essentially all of the Cisco outcrop belt in Eastland, Stephens, Callahan, Throckmorton, Shackelford, Young, Jack, Montague, and Clay Counties has been mapped at scales of 1:20,000 or 1:62,500. Approximately 400 measured sections and 800 described localities have been utilized in outcrop studies to date. Surface and subsurface studies cover all or parts of 23 counties or approximately 20,000 square miles. Subsurface control consists of 4,000 mechanical well logs, but limited sample and core data. The regional stratigraphic framework consists of parallel dip sections from outcrop to basin spaced 6 to 8 miles apart with strike sections spaced about 15 miles apart; all wells were correlated within the gridlike stratigraphic framework.

Methods used in facies analysis include fundamental stratigraphy and mapping, studies of sedimentary structures, petrographic study of limestones and sandstones, clay-mineral analyses, general paleoecologic work, structural studies, decompaction analysis, and isopach-mapping of individual sandstone bodies.

GENERAL DEPOSITIONAL HISTORY

By the time of late Missouri and early Virgil deposition, subsidence in the Midland Basin (fig. 1), relative to the stable Eastern Shelf (site of the earlier Concho Platform), had produced significant bathymetric relief between shelf (fig. 3) and basin. Cisco fluvial-deltaic systems prograded across subjacent Canyon shelf and bank limestones (fig. 43). Deltas provided sediment to point sources on the shelf edge where it was then moved down the basin slope by turbidity currents and associated processes to produce thick, laterally accreting slope wedges. These wedges filled a principal part of the eastern Midland Basin (fig. 44).

A wide variety of fluvial-deltaic facies can be delineated in the subsurface (fig. 45) and can be more intensively examined in outcrop (fig. 46). As the eastern flank of the basin was filled by basinward accreting slope wedges, the sediment dispersal system migrated westward, resulting in a basinward shift in the facies tract. Consequently, lower Cisco facies in outcrop are dominantly deltaic-marine (fig. 46B), while upper Cisco facies in outcrop are principally fluvial-marine (fig. 46A).

About 10 to 15 principal fluvial-deltaic progradational episodes can be recognized within the Cisco system. Following termination, each delta system was transgressed by nearshore destructional sandstones and finally by open-shelf limestone facies. The various fluvial-deltaic systems display remarkably similar regional distribution patterns (e.g., figs. 47-51): a basinward progression from complex beltlike, fluvially dominated facies downslope to simpler, distributive deltaic patterns near the terminus of the system. Each system supplied sediment to slope and basinal systems at one or more point sources along the shelf edge.

During early Virgil deposition, the sediment supply to the basin gradually increased; coincident with the increase in sediment supply was an increase in the rate of basin subsidence. Basin subsidence and the rate of terrigenous clastic sedimentation reached a maximum in late Virgil

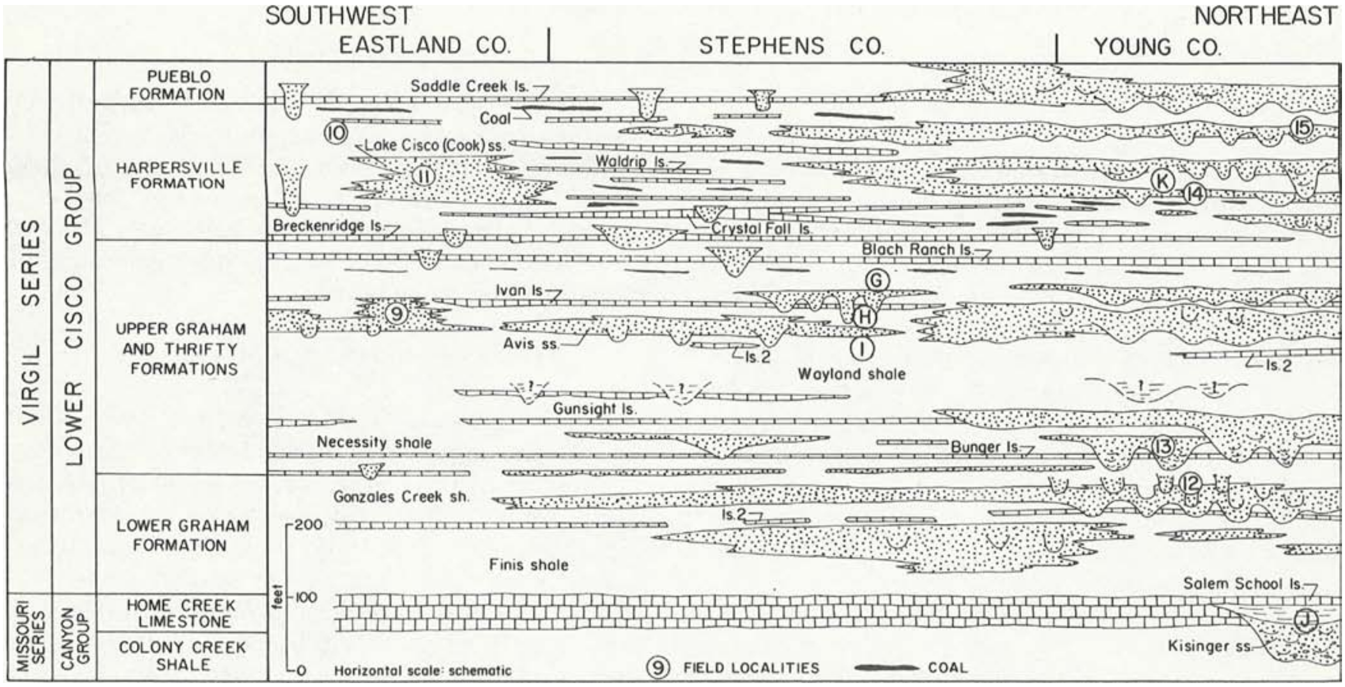

Figure 41. Schematic facies cross section along outcrop, Cisco Group, North-Central Texas. Based on detailed mapping and 350 measured sections. Surface data contributed by McGowen (1964), Waller (1966; personal communication, 1973); and Galloway and Brown (1972).

when the thickest accretionary slope wedge (Gunsight to Breckenridge equivalent) prograded about 15 miles into the deep Midland Basin (fig. 44; pl. I). During Wolfcamp deposition, the rate of sediment supply gradually diminished and subsidence of the Midland Basin decelerated; consequently, slope wedges gradually decreased in thickness and the rate of slope progradation diminished markedly. By the end of Wolfcamp deposition, the Eastern structural shelf of North-Central Texas had become primarily a carbonate-evaporite-tidal flat province with terrigenous sediments supplied only by minor delta systems.

In summary, terrigenous clastic sediment was deposited in depositional systems ranging from fluvial to slope and basin (fig. 52). The spatial distribution of these systems indicate that deposition in each occurred contemporaneously throughout the region (fig. 53). Enormous volumes of terrigenous clastic sediment passed through fluvial and deltaic systems en route to principal depositional sites on the basin slope (fig. 54); shelf deposition was essentially restricted to shelf-edge limestone systems. Thin limestone bodies pinch out upslope into areas of dominantly fluvial-deltaic facies. Approximately 75 percent of all Virgil and Wolfcamp terrigenous clastics that reached North-Central Texas by-passed the Eastern Shelf and were stored in the large accretionary slope systems.

DEPOSITIONAL SYSTEMS

Assemblages of facies that have been grouped genetically on the basis of inferred sedimentary processes and environments are called *depositional systems* (Fisher and McGowen, 1967). The following systems will be considered in terms of facies composition, distribution, and role in basin filling: Cisco fluvial-deltaic system (and associated interdeltaic areas); Sylvester shelf-edge-bank system; Sweetwater slope system; and Midland Basin system (fig. 5, pl. I).

CISCO FLUVIAL-DELTAIC SYSTEM

Within stable cratonic basins, it is difficult to map separately fluvial and deltaic facies because the two systems are commonly superposed (fig. 46). Deltaic and fluvial systems in unstable basins tend to stack vertically in discrete segments along paleoslope (fig. 23A); however, extensive progradation in unusually stable cratonic basins results in superposition of deltaic and fluvial systems (fig. 23B). In addition, the fluvial channels tend to erode deeply into subjacent deltaic facies. Superposition of the two systems is common in upslope (outcrop) areas, but there is a general decrease in fluvial facies basinward where deltaic facies have been less cannibalized by subsequent, superimposed fluvial channels of the same river system.

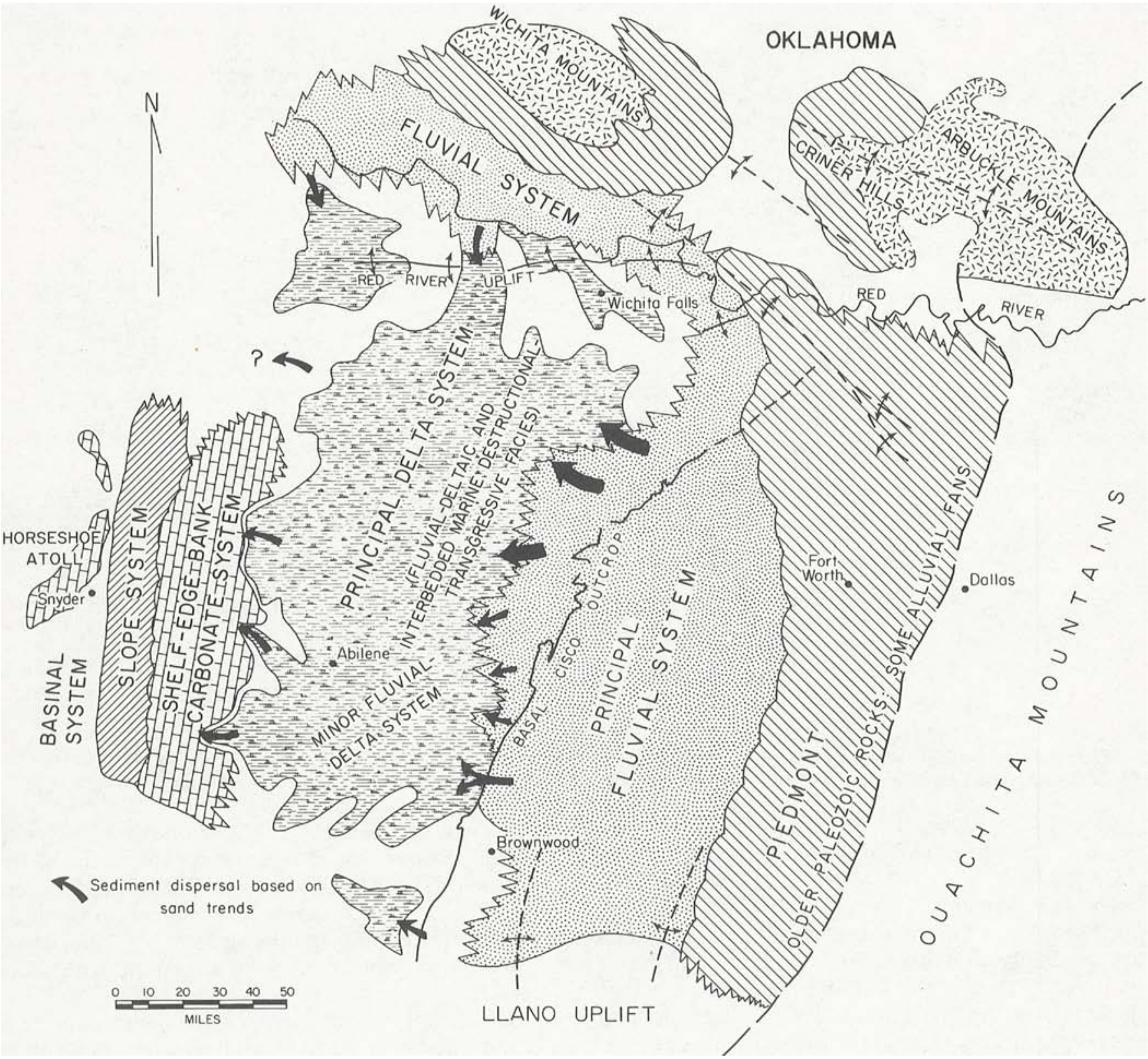

Figure 42. Middle Cisco depositional systems: Cisco fluvial-deltaic system; Sylvester shelf-edge-bank carbonate system; Sweetwater slope system; and Midland Basin system. Oklahoma sources after Wermund and Jenkins (1970).

Fluvial Systems

In upslope areas, Cisco fluvial facies (figs. 47-51) are tabular to sheetlike complexes of anastomosing sandstones; braided or coarse-grained meanderbelts are common upslope near source areas. Downslope, narrower, fine-grained meanderbelt sand bodies become more common, and they grade distally into relatively straight distributary-channel deposits (figs. 8, 9). Valley-fill facies develop on upper delta plains and alluvial plains; erosion may cut into marine facies of an earlier cycle. Because of repeated and irregular progradations, the Cisco fluvial facies tract shifted considerably along paleoslope; as a result, a mixture of various kinds of fluvial systems can be found in outcrop.

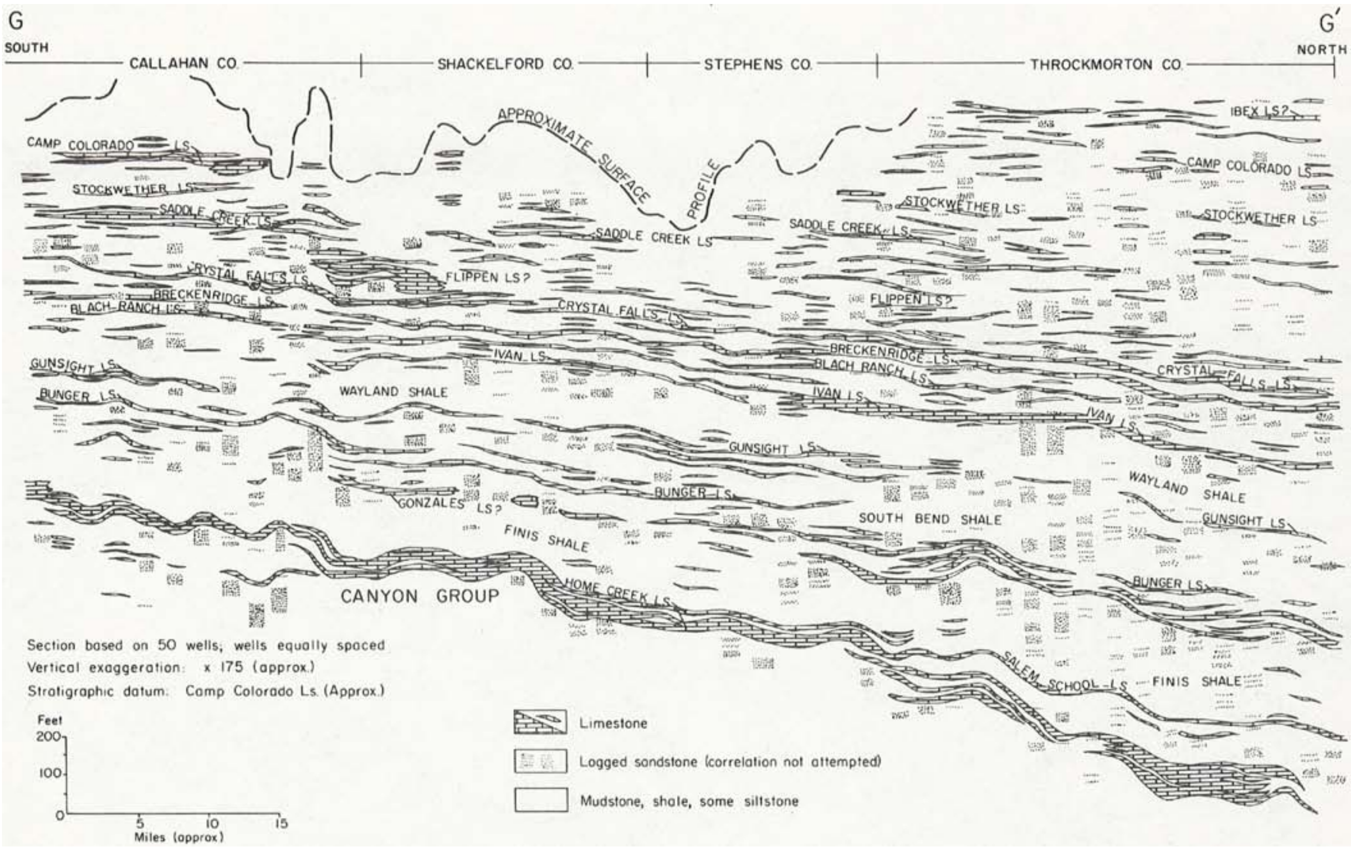

Figure 43. Subsurface cross section G-G′ (strike) from Callahan to Throckmorton Counties, Texas, showing facies of the Cisco Group. Based on 50 wells. See fig. 4 for line of section. Data on open-file, Texas Bureau of Economic Geology.

Braided systems.—Cisco braided streams developed principally east of the present outcrop (fig. 42), probably as a series of high-gradient, coalescing streams originating in the uplifted Ouachita and adjacent source areas. Braided facies are unusually well preserved in southern Oklahoma and they extend into Texas where they are best developed in middle Cisco rocks of Montague and Jack Counties. Where Cisco rocks crop out essentially parallel to paleoslope (figs. 47-51) in eastern Young, Jack, and Montague Counties, evidence exists to indicate progressive erosional truncation of units to the northeast. This northeast truncation reflects progressive structural uplift in the Ouachita fold belt and eastern Fort Worth Basin, and it coincides with a corresponding increase in braided, coarser grained facies.

Braided facies are composed of medium- to coarse-grained sandstone and conglomerate with chert pebbles up to 3 inches in diameter (fig. 73B). Trough cross-beds of all scales are common; tabular foreset cross-beds and horizontal stratification are also common (refer to table 1 for a petrographic summary of the facies). The problem of differentiating braided facies from distributary fill in the subsurface by E-log patterns is illustrated in figure 45 (C-1, C-2). Proper subsurface recognition requires information on the geometry of the sandstone body (tabular or elongate), along with other factors.

Deposition is inferred to have occurred within broad, shallow, braided channels by deposition associated with longitudinal and transverse bars (figs. 10; 15A). Resulting sandstone geometry is tabular or multilateral; very little mud occurs within a braided system. At Locality 11C is an example of a braided stream deposit.

Coarse-grained meanderbelt systems.—Typical coarse-grained systems have not been recognized in the Cisco, but varieties of coarser grained meanderbelt facies (figs. 72, 73C) represent sedimentation in moderately sinuous streams; possible chute channels have been observed but chute bars have not been recognized (figs. 11; 15C). Many Cisco fluvial facies are intermediate in the spectrum between braided and fine-grained meanderbelts.

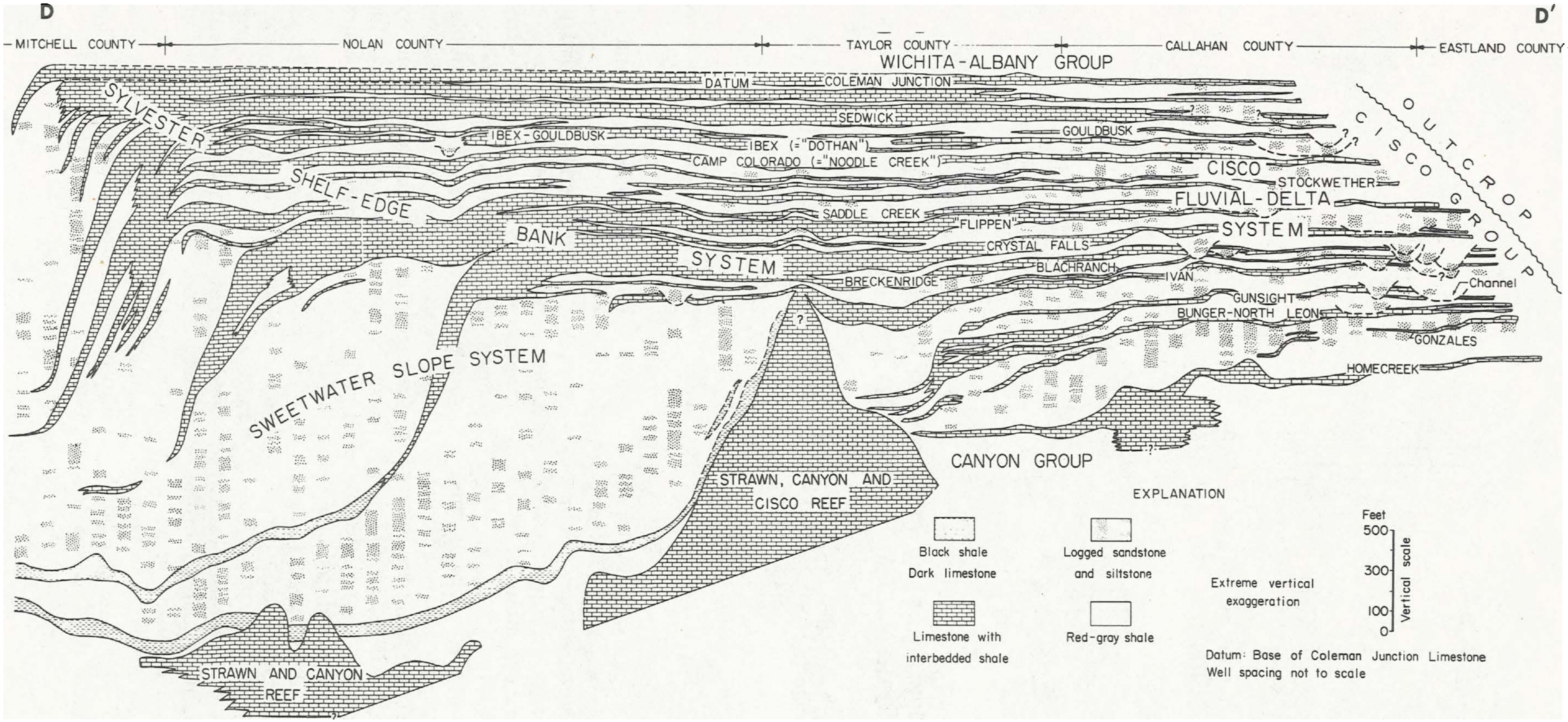

Figure 44. Subsurface cross section D-D′ (dip) from Mitchell to Eastland Counties, Texas, showing facies of the Cisco Group. Based on 60 wells. After Brown (1969d); see fig. 4 for line of section. Data on open-file, Texas Bureau of Economic Geology.

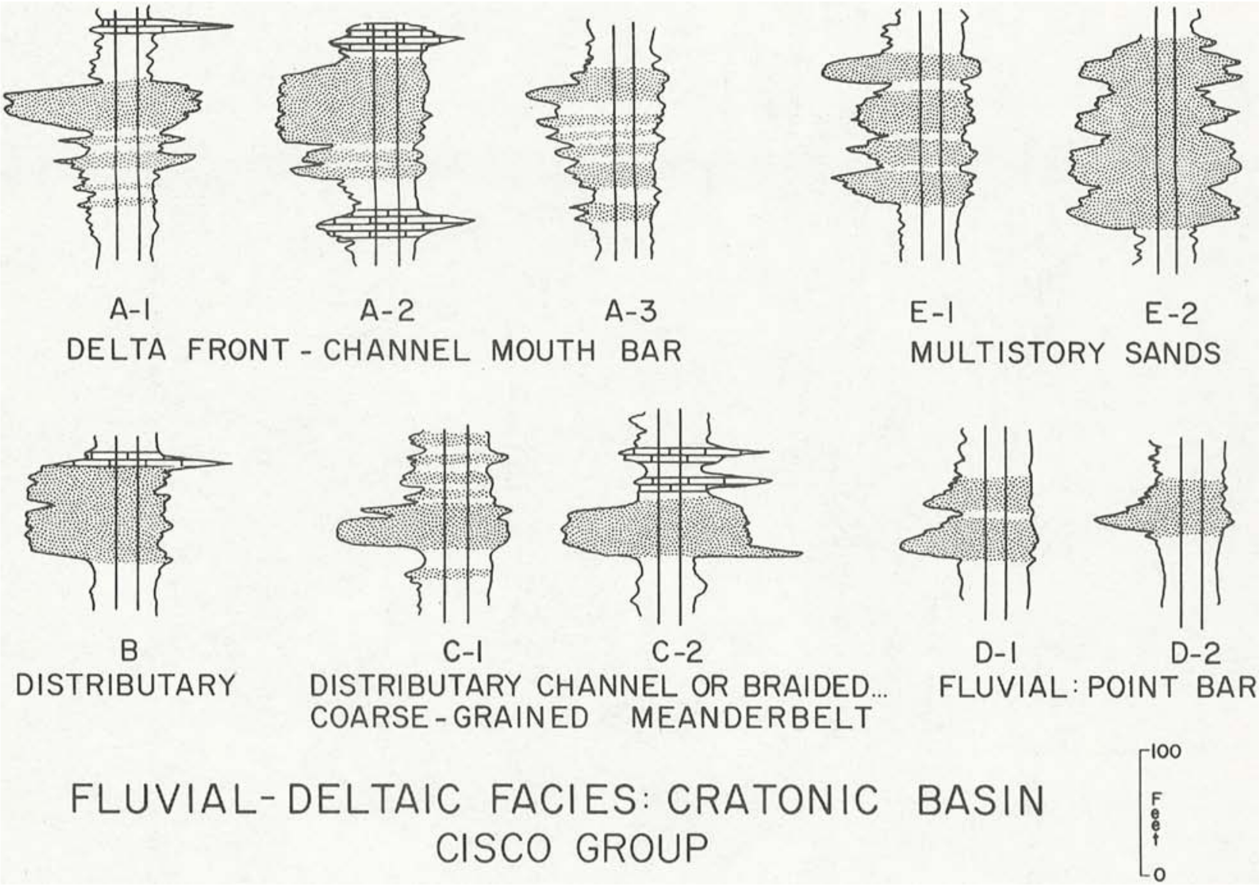

Figure 45. Typical E-log patterns of facies within Cisco fluvial-deltaic system, North-Central Texas. Compiled by W. E. Galloway (Brown, 1969d).

Point bars in these systems are not well developed, especially in the uppermost bar; moderate sinuosity may account for the general absence of upper bar structures; grain size is also medium to coarse (refer to table 1 for a petrographic summary of the sandstones).

The problem of differentiating coarse-grained meanderbelt sediments from distributary-channel-fill deposits in the subsurface by E-log patterns is illustrated by figure 45 (C-1, C-2); recognition depends upon the geometry of the sandstone, either tabular (braided) or elongate (distributary), along with other factors. At Localities 11A and 11B are exposures of a coarse-grained point bar.

Fine-grained meanderbelt systems.—These facies are probably more common in outcrop than have been recognized, but they occur principally in the subsurface near the basinward termination of the fluvial facies tract (figs. 47-51). Sandstone bodies contain channel-lag gravel and fine-grained point bars in slightly sinuous to straight belts up to 2 or 3 miles wide.

Fining-upward grain size and a coincident decrease in scale of sedimentary structures characterizes the sandstones (figs. 12; 15D). This vertical sequence includes (upward) large- to medium-scale trough cross-beds, large- to moderate-scale tabular foreset cross-beds, small-scale tabular and trough cross-beds, and ripple or ripple-drift cross-laminations. Levees, where preserved, cap the sequence. The meanderbelts occur within red and maroon overbank mudstones and may yield distinctive E-log patterns in the subsurface (fig. 45, D-1, D-2).

The sandstones are dominantly siliceous, well-sorted siltstone and fine- to very fine-grained sandstone (table 1). The accretionary or epsilon bedding that typifies point bars is normally well preserved (fig. 79). Individual channel deposits are asymmetric in cross-section; point bars are commonly superposed with successive channels eroded into underlying bar deposits (fig. 45, D-1, E-2). At Locality 15 is an example of a fine-grained point-bar deposit.

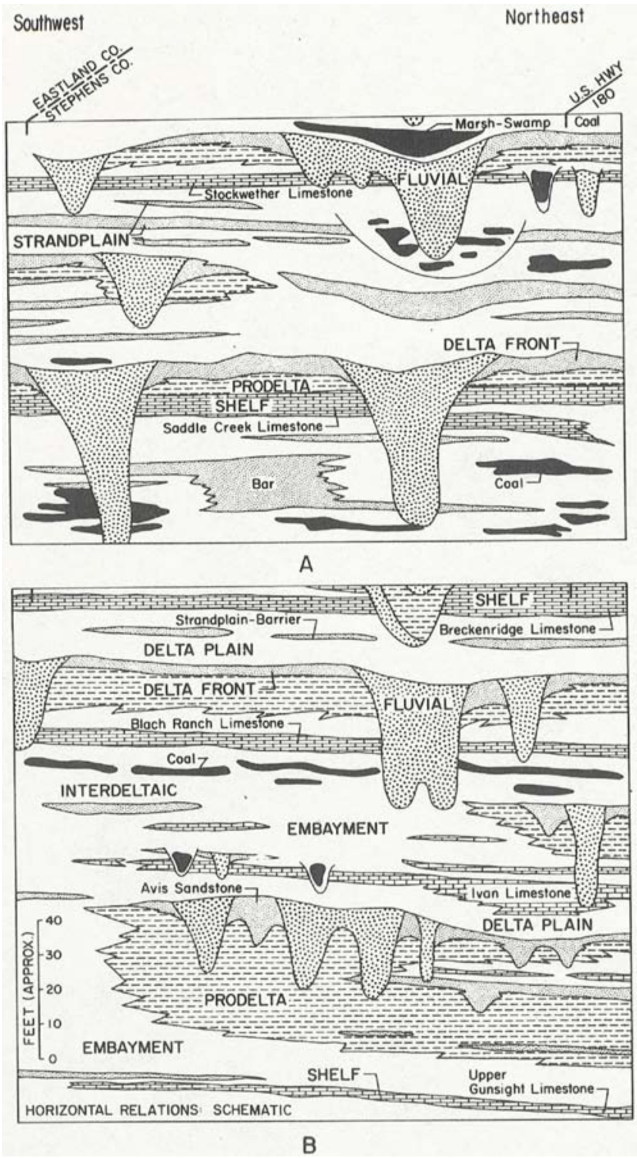

Figure 46. Nature of outcropping cyclic facies, Cisco Group, Stephens County, Texas. A. Fluvially dominated marine-nonmarine cycles, upper part of Cisco Group. B. Delta-dominated marine-nonmarine cycles, lower part of Cisco Group. Based on detailed mapping and 350 measured sections.

Distributary-channel-fill facies.—Symmetrical channel-fill Cisco sandstones of inferred distributary origin occur at the top of many deltaic sequences (fig. 75). This facies is most common in the subsurface near the distal end of the fluvial facies tract (figs. 47-51). Deposits are fine- to medium-grained, trough-cross-bedded sandstones that exhibit no vertical textural or sedimentary structural variations (figs. 13, 15B). In the subsurface, this uniform vertical character makes the differentiation of distributary and braided/coarse-grained facies dependent upon geometry and core data rather than on E-log patterns (fig. 45, C-1, C-2).

The channel fill is commonly deformed by compaction (fig. 75). The channel may erode delta-plain facies, or it may overlie channel-mouth-bar facies (fig. 13). At Locality 13 is an example of a distributary-channel-fill sandstone.

Valley-fill fluvial facies.—Relatively shallow Cisco erosional valley-fill facies are superimposed onto upper delta-plain or alluvial-plain facies as the result of changes in the profile of equilibrium (fig. 14). These facies are common in middle Cisco rocks of eastern Young, Jack, and Montague Counties, where uplift caused progressively greater erosion eastward toward source areas. Valley-fill facies also occur elsewhere along outcrop, but depth of erosion is commonly less than 30 feet.

The valley-fill contains trough cross-beds; a vertical upward fining occurs from coarse gravel to medium-grained sand; there is a coincident upward decrease in scale of troughs (fig. 76). Like distributary-channel deposits, valley-fill deposits also exhibit evidence of confined flow but grain size is much coarser than within the distributary deposits. At Locality 13 is an example of valley-fill facies.

Delta Systems

High-constructive Cisco delta systems, similar to Holocene Mississippi varieties (fig. 16), have been inferred from facies analysis in North-Central Texas. Deltaic facies resemble both the elongate (figs. 17; 20A) and the lobate (figs. 19; 20B) varieties. Both types have been recognized within the same Cisco delta complex. Differentiation of elongate and lobate varieties is based on external geometry and on the nature of delta-front and channel-mouth-bar facies, as well as on the type of contemporaneous deformation affecting delta-front facies; i.e., growth faulting (lobate) and extremely deformed and intruded bar-finger sediments (elongate). Most Cisco deltas are elongate; lobate deltas are minor lobes commonly associated with the rapidly prograding elongate variety.

The distribution of Cisco delta systems on the Eastern Shelf (e.g., figs. 47-51) is controlled by several factors (Brown, 1969c): 1) effect of subjacent Canyon carbonate-bank paleotopography; 2) the effect of belts with differential rates of structural subsidence; and 3) most commonly, by the effect of differential sand/mud compaction on paleotopography. Several thick Canyon limestone

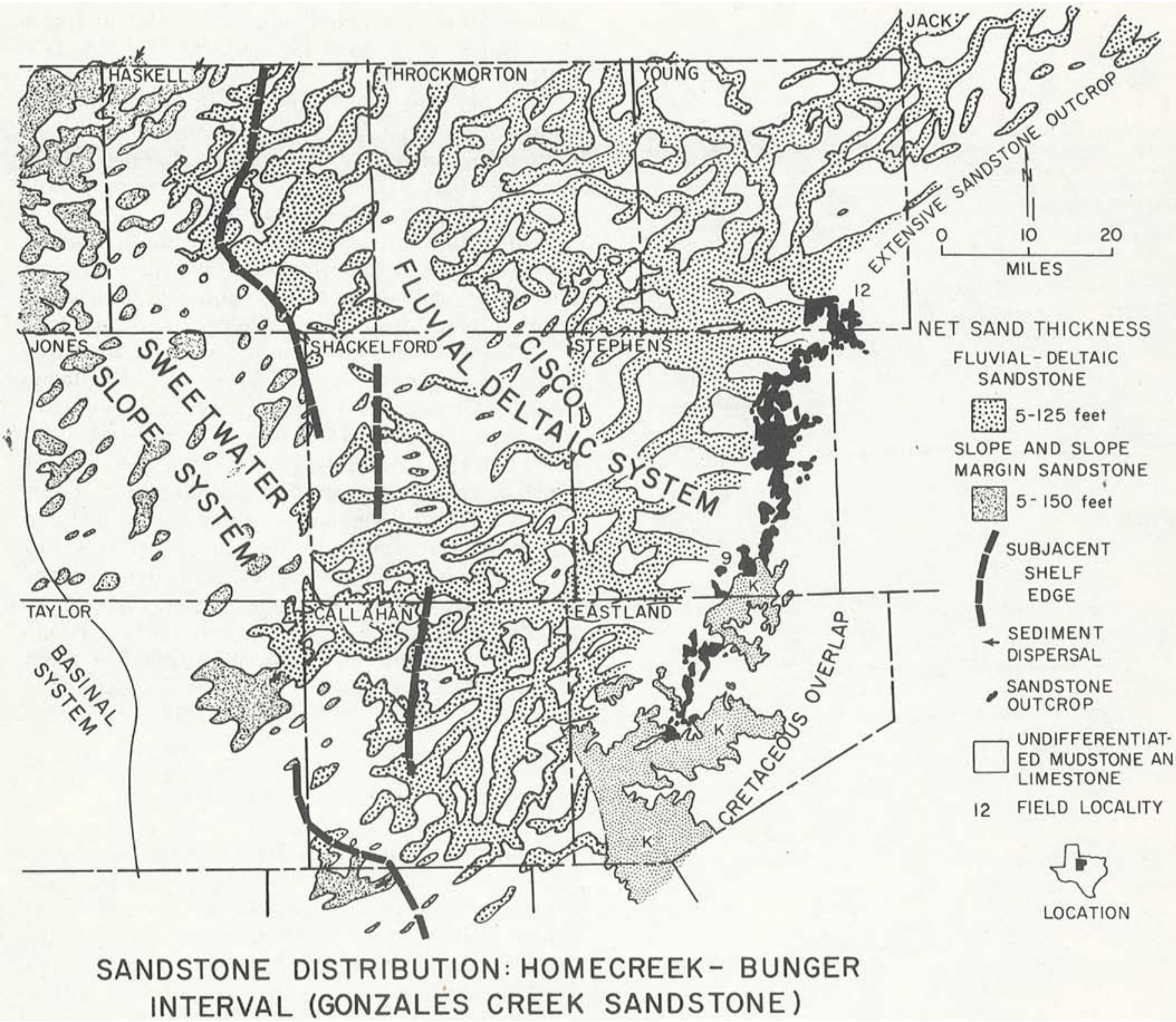

Figure 47. Net-sandstone map, Gonzales Creek Sandstone, Cisco Group, North-Central Texas. Subsurface control based on 3,500 wells; data on open-file, Texas Bureau of Economic Geology.

banks (figs. 32, 35, 38) exerted control on the route of initial Cisco Gonzales Creek delta progradation (fig. 47). The northeast-southwest trend of Canyon carbonate banks was inherited by Cisco deltaic systems and the trend was generally perpetuated in a vertically offsetting manner by differential compaction. The relative permanence of the sites of several delta systems throughout the Strawn, Canyon, and Cisco suggest contemporaneous structural control. Similarity of paleoslope throughout the Cisco is evident from net-sand maps of various fluvial-delta systems (figs. 47-51).

High-constructive elongate deltas.—These deltas occur at several stratigraphic positions, but they are best preserved at outcrop in the lowermost part of the Cisco Group, particularly within the Graham Formation.

Individual elongate-delta sandstone bodies in the Cisco are characterized by their 1) highly deformed delta-front and channel-mouth-bar facies; 2) straight and narrow (300 to 1,000 feet wide) external geometry; and 3) a low width/thickness ratio. These unique sandstone bodies, which were called bar fingers by Fisk (1961), are composed of superposed delta-front, channel-mouth-bar, and distributary-channel facies (fig. 18). The unique geometry results from rapid subsidence of the debouched sand into underlying prodelta mud.

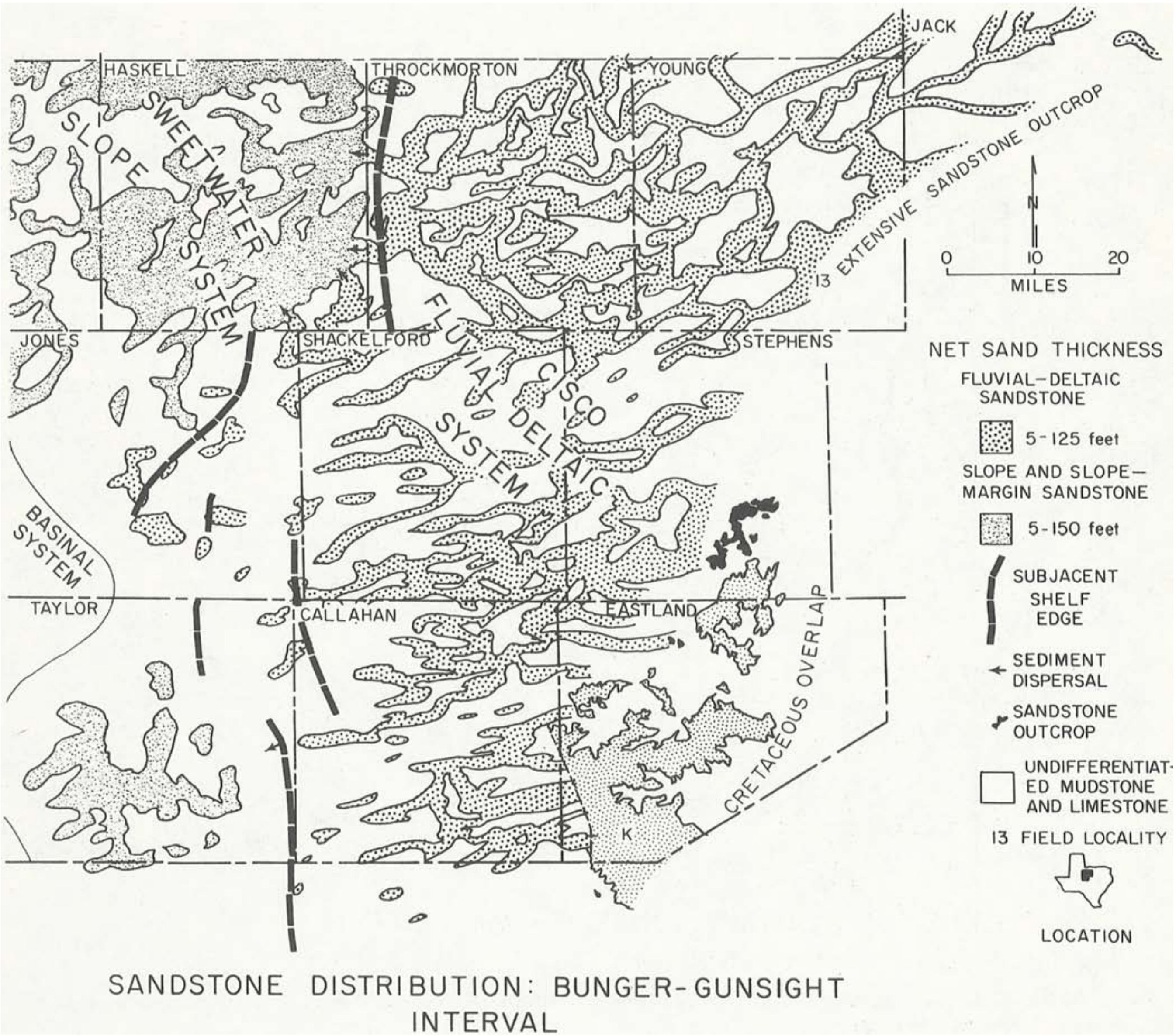

Figure 48. Net-sandstone map, post-Bunger—pre-Gunsight Sandstone, Cisco Group, North-Central Texas. Subsurface control based on 3,500 wells; data on open-file, Texas Bureau of Economic Geology.

Because of the rapid subsidence, little sand is reworked into delta-front facies; most of it is preserved in a channel-mouth bar. As a result, Cisco bar fingers display an abrupt transition from proximal prodelta (with frontal splays and flow rolls) to massive bar-finger sandstone; distributary-channel-fill deposits may be superimposed on the channel-mouth bar (fig. 20A).

The vertical sequence in Cisco elongate deltas is similar to that of the modern Mississippi birdfoot, except in scale. Upward the facies are (fig. 20A): 1) prodelta mudstone, plant-rich, with proximal (upper) flow rolls; 2) massive bar-finger sandstone with highly deformed internal structure including folds, faults, and diapiric intrusions; 3) superimposed distributary-channel fill that may be highly deformed; 4) delta-plain facies such as interdistributary mudstones that are locally fossiliferous, thin coal beds, fresh-water limestones and marls, and crevasse-splay sandstones; 5) destructional, marine-reworked, burrowed sandstones; and 6) transgressive marine limestones. The more massive bar-finger sandstones with minimum basal gradation with prodelta facies can be observed on some E-logs (fig. 45, A-2).

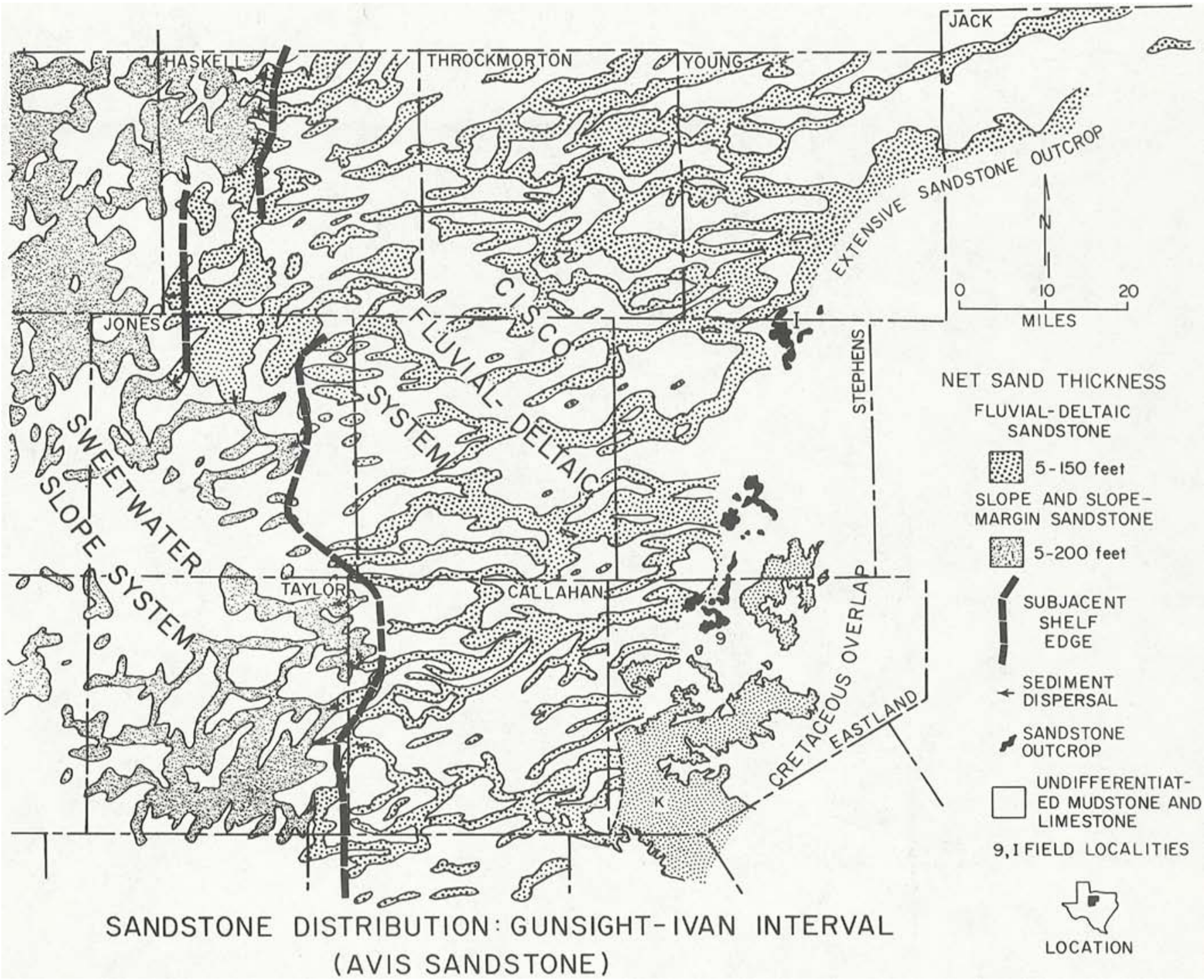

Figure 49. Net-sandstone map, Avis Sandstone, Cisco Group, North-Central Texas. Based on 3,500 wells; data on open-file, Texas Bureau of Economic Geology.

This type of delta system occurs at Locality H; bar-finger sandstones also occur locally within the Avis system near Locality I; and the facies is common within the Gonzales Creek Sandstone of northern Stephens and southeastern Young Counties, where it probably underlies the distributary-channel-fill facies at Locality 12. Bar-finger sandstones are poorly exposed in North-Central Texas; large contorted blocks commonly break away and roll down slopes of the subjacent prodelta facies.

Prodelta facies beneath bar-finger deposits are not unusually thicker than prodelta beneath lobate deltas; it is inferred that rapid, continuous deposition, with excessive overloading of the channel-mouth bar, coupled consequently with rapid progradation over still highly uncompacted muds, are critical factors that cause the complete soft-sediment (or plastic) failure of deltaic sands. Discontinuously deposited minor lobate deltas consequently prograded slowly because of low, periodic discharge; prodelta-mud facies were sufficiently compacted so that failure due to bar-loading was resolved more slowly by growth-fault motion.

High-constructive lobate deltas.—These Cisco deltas are well exposed at several localities in North-Central Texas (Localities 9, I). They are characterized by unusually well-bedded and well-developed delta-front facies; probably because of discontinuous discharge, marine processes extensively reworked channel-mouth-bar facies into

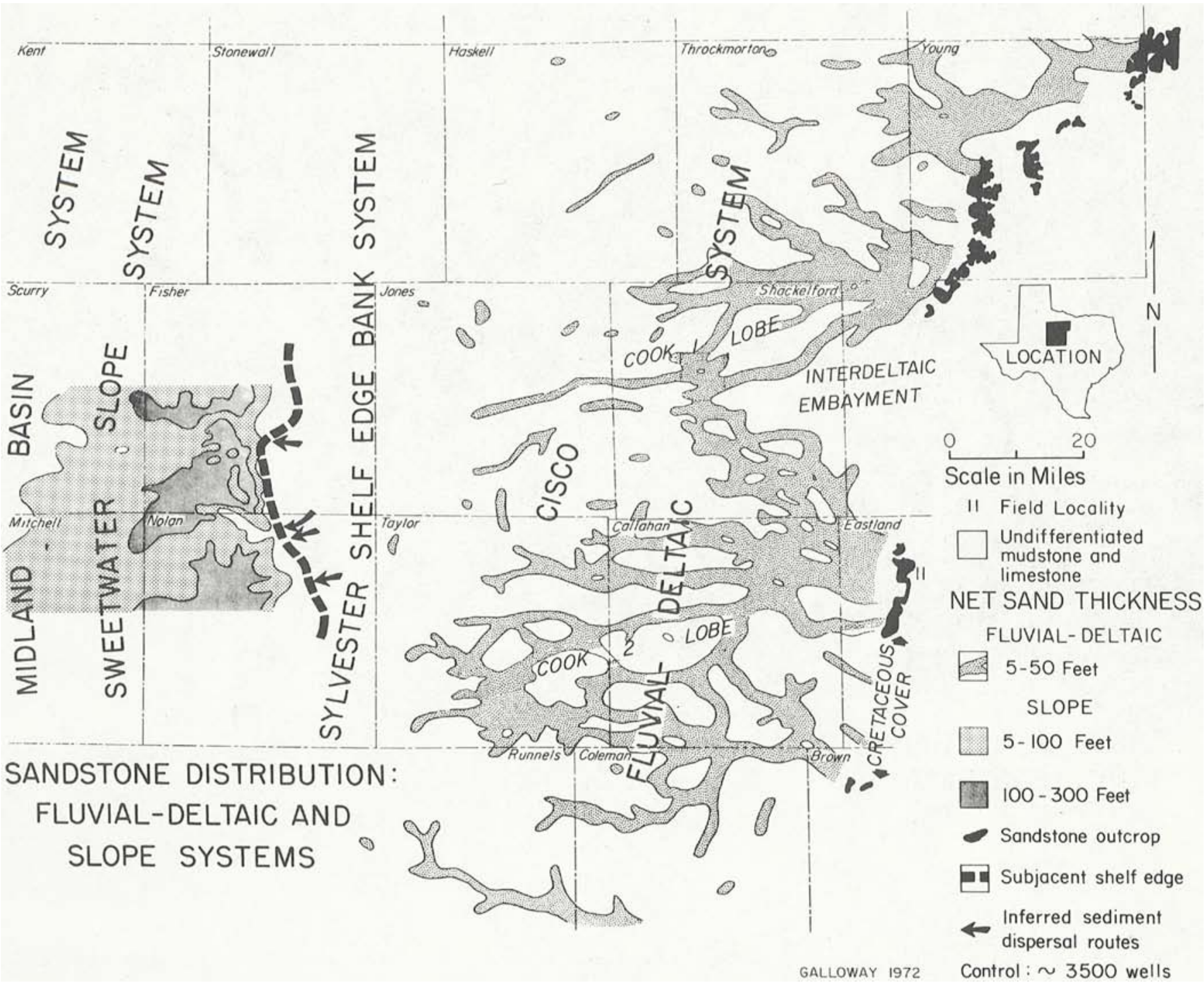

Figure 50. Net-sandstone map, lower Cook Sandstone, Cisco Group, North-Central Texas. Based on 3,500 wells; data on open-file, Texas Bureau of Economic Geology. After Galloway and Brown (1972, 1973); reprinted with permission, American Association of Petroleum Geologists.

sheetlike, well-bedded delta-front facies (fig. 69). Growth faulting is commonly associated with these systems. Although discharge is apparently more discontinuous in lobate deltas, this does not preclude the periodic deposition of large volumes of sediment during peak discharge.

Channel-mouth-bar and adjacent delta-front sandstones exhibit apparent horizontal bedding (high flow regime), although the bedding may consist of parallel layers deposited from short-lived suspension of sand over the bar crest. Vertical ripple-drift cross-lamination and flame structures similarly indicate the high energy available on the channel-mouth bar during high but periodic discharge.

A vertical sequence (upward) through a Cisco lobate delta includes (fig. 20B): 1) plant-rich prodelta mudstones with proximal (upper) flow rolls and a gradual intergradation with overlying delta-front facies; 2) sheetlike delta-front sandstones with ripple-drift cross-laminations, flame structures, horizontal bedding, and wave ripples; 3) channel-mouth-bar sands (thicker than delta-front beds) that display horizontal laminations and growth faults; and 4) delta plain; 5) destructional, and 6) transgressive facies similar to those of elongate deltas, except that destructional bars (sandstones and calcarenites) more commonly fringe lobate deltas. Lobate sandstone bodies exhibiting extensive intergradation with subjacent

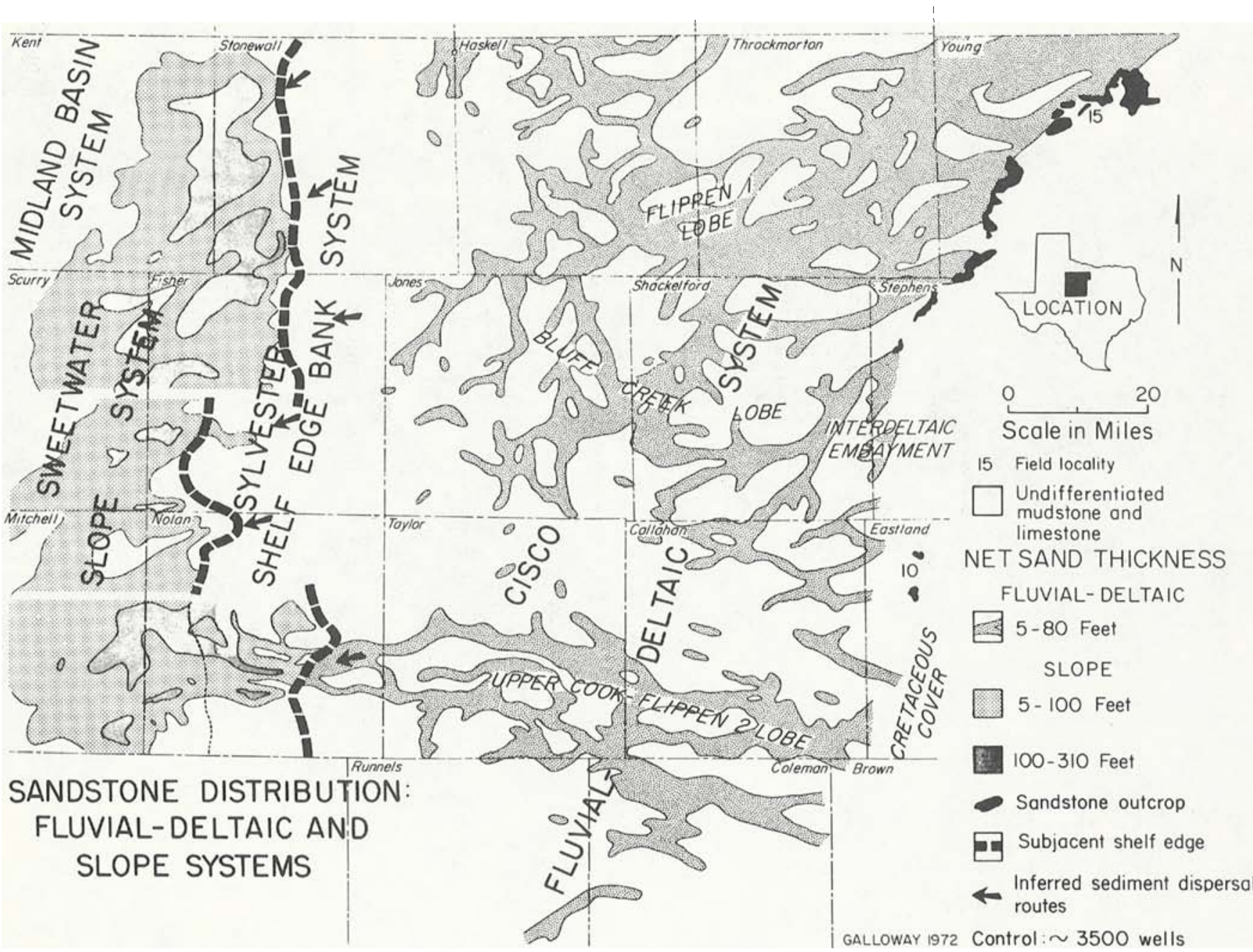

Figure 51. Net-sandstone map, upper Cook-Flippen Sandstone, Cisco Group, North-Central Texas. Based on 3,500 wells; data on open-file, Texas Bureau of Economic Geology. After Galloway and Brown (1972, 1973); reprinted with permission, American Association of Petroleum Geologists.

prodelta mudstones can be recognized on some E-logs (fig. 45, A-1, A-3).

Interdeltaic-embayment facies.—Coastlines between principal Cisco delta lobes (fig. 21) were sites of basinward mudstone and sandstone accretion by mudflats and along strand plains. Embayment sequences also include brackish-bay mudstones and limestones, and thin coal beds. Embayment facies and seqences of events are genetically tied to delta development (fig. 22). Specific details of a Harpersville embayment were described by Galloway and Brown (1972), but the sequences occur adjacent to each principal deltaic lobe. Localities 10 (fig. 70), 14, and K (fig. 78) illustrate some of the varieties of embayment facies.

Cisco embayments filled with strike-fed sediment during delta progradation, chiefly as accretionary mudflats and chenierlike strand plains; local bays contained brackish-water faunas. Following delta abandonment, thin barriers (beach and berms with thin shoreface) developed as destructional islands or shoals that were locally supplied with relict sediment, as well as sediment reworked from adjacent foundering deltas. Lagoons and lakes landward of the thin barriers were sites of detrital coal deposition. The embayment was eventually filled with open-shelf limestone.

The broad embayments, therefore, were filled with repetitive sequences that reflect brackish bays, mudflats, strand plains, thin coals, minor barriers, and marine facies. For the stratigraphy of Harpersville embayment, see Brown (1959) and McGowen (1964). The petrography of these sheet-

SANDSTONE FACIES		Sheet sandstone facies			Channel sandstone facies			
		Upper	Lower	Undifferentiated	Channel core	Middle-upper point bar	Braided/coarse meandering	Bioturbated beds
Color class	5-YR	27	15	17	33	31	31	0
	10-YR	18	38	25	25	23	69	25
	5-Y	45	46	40	25	38	12	50
	Other	9	8	21	16	15	12	50
Cement	Siliceous	91	92	54	83	85	94	38
	Calcareous	55	31	37	0	0	0	38
	Chloritic	9	0	21	0	0	0	25
Sorting	Poor to moderate	0	15	13	50	15	62	38
	Well	64	38	67	42	77	37	62
	Very well	36	38	17	8	8	6	12
Grain size	Siltstone and very fine sandstone	36	62	46	8	54	6	87
	Fine sandstone	64	23	51	8	31	25	12
	Medium to coarse sandstone	0	8	4	76	15	37	0
	Conglomeratic sandstone	0	0	0	8	0	31	0
Mineralogy	Quartzarenite	91	77	92	32	61	36	100
	Slightly cherty quartzarenite	0	8	4	23	38	24	0
	Subchertarenite	9	15	4	23	0	30	0
	Chertarenite	0	0	0	23	0	11	0
	Total number of samples	11	13	24	12	13	16	8

Table 1. Petrographic properties of fluvial-deltaic sandstone facies. Numbers indicate the percent of the total number of samples in each facies (column) that exhibit the particular property (row). Because some samples may exhibit several colors or cements, column totals may exceed 100 percent. (From Galloway and Brown, 1972.)

like embayment sandstones contrasts sharply with fluvial facies (table 1). Embayment-mudstone facies contain the most abundant invertebrate faunas in North-Central Texas.

SYLVESTER SHELF-EDGE-BANK SYSTEM

In the absence of Cisco deltaic deposition, particularly in areas near the western edge of the Eastern Shelf, limestone deposition dominated (figs. 42, 44). During early Virgil deposition, large volumes of sediment supplied to the area precluded extensive limestone deposition (fig. 44); as sediment supply from the east declined in late Virgil and Wolfcamp, however, shelf-edge-limestone facies reached thicknesses of several hundred feet. Fluvial-deltaic deposition was concentrated in upslope areas (figs. 43, 47-51) where tongues of shelf limestone are thin; only principal deltas prograded to the shelf edge, and these deltaic clastics split the thick shelf-edge banks.

Limestone banks intertongue upslope with fluvial-deltaic clastics and limestones intertongue basinward with slope facies; extensive tongues of limestone debris (limestone turbidites) that drape over the upper and middle slope (fig. 44) provide stratigraphic markers that permit subdivision and mapping of slope wedges.

The carbonates are massive and near shelf edges they commonly have been dolomitized. Galloway and Brown (1972) described the Sylvester system. Shelf-edge-bank facies shifted basinward through time as the Sweetwater slope system filled the basin (pl. I).

SWEETWATER SLOPE SYSTEM

An extensive study of the Sweetwater system (Galloway and Brown, 1972, 1973) shows that thick slope wedges prograded into the eastern part of the Midland Basin as terrigenous clastic sediment was supplied principally by deltaic systems. Although these facies do not crop out in North-Central Texas they are important in any consideration of sediment dispersal because 75 to 80 percent of the Virgil and Wolfcamp terrigenous clastics in the region ultimately were deposited in slope environments (fig. 44, pl. I). Depth of water ranged from 500 feet during early Virgil deposition to 1,500 feet during late Virgil deposition when maximum depths occurred; these figures do not include the effects of compaction on the slope wedges. During deposition the slopes were inclined basinward from 1.5 to 5 degrees, the approximate inclination of Holocene continental slopes.

Net-sandstone maps of several Cisco fluvial-deltaic systems (figs. 47-51) point to direction of sediment supply. Sandstones can be directly traced from delta to slope in several cases, but in others it is possible that tidal currents transported sediment from shelf-terminating deltas to the shelf edge.

Sediment that reached the edge of the shelf moved through a series of environments (fig. 54). Progradational shelf-margin sandstones that resemble delta-front facies were fed by aggradational channels similar to distributary channels; these shelf-margin facies were deposited either in terminal deltaic environments or in ebb-tidal deltas, depending upon the means by which sediment was transported across the shelf-edge banks. These facies are inferred to be of slope origin rather than prodelta origin because the principal sedimentary process was resedimentation by mass gravity or turbidity flow rather than by prodelta suspension deposition directly from distributaries. Even though some turbidity and mass gravity processes operate on prodelta slopes, especially those building into deep water, the processes account for only a small part of the prodelta wedges. Prodelta facies simply will not prograde into 1,500 feet of water without resedimentation becoming a primary process; thus, genetically, the thick wedge is dominantly of slope origin.

Sediment deposited at the edge of the shelf moved downslope by mass gravity movement, by turbidity flow, and apparently by some traction transport (fig. 54). Sand was funneled primarily through slope-trough channels to distal-slope submarine fans. Sediment arriving on the slope from one or several localized point sources formed compound fan-cones composed of a basinward progression of facies from shelf-margin sandstones, slope-trough sandstones (and adjacent fan-plain mudstones), to distal turbidite fans composed of silty and sandy mudstones. In dip cross section, compound fan-cones are wedges of slope sediment (figs. 44, 52) that accreted basinward. In cratonic basins, fan wedges prograde laterally into the basin (offlap), but in rapidly subsiding basins, the fan wedges tend to stack vertically. These slope-constructional or progradational episodes coincided with direct supply of fluvial-deltaic sediment to the shelf edge. When the delta system shifted by avulsion, slope progradation or construction diminished and a destructional phase was established in the area, during which time the slope profile was reduced by slumping with consequent onlap of distal slope facies (similar to continental rise). Final destruction was marked by a stable slope and deposition of aprons composed of limestone turbidites (derived from shelf-edge bank) over the terrigenous clastic slope surface (fig. 53).

A complete, idealized dispersal system with characteristic E-logs (fig. 54) illustrates the construction of compound fan-cones or slope wedges.

MIDLAND BASIN SYSTEM

Virgil and Wolfcamp basinal facies (excluding slope deposits) are composed principally of thin, siliceous, black shales and some impure, dark limestones (figs. 44, 52, pl. I). The basin was essentially sediment-starved; the principal input was by pelitic and pelagic deposition from suspension. Basinal facies grade shelfward into distal turbidite sediments of the slope system (fig. 54).

Dark, thin, pelagic limestones display sharp resistivity profiles on E-logs; these limestones

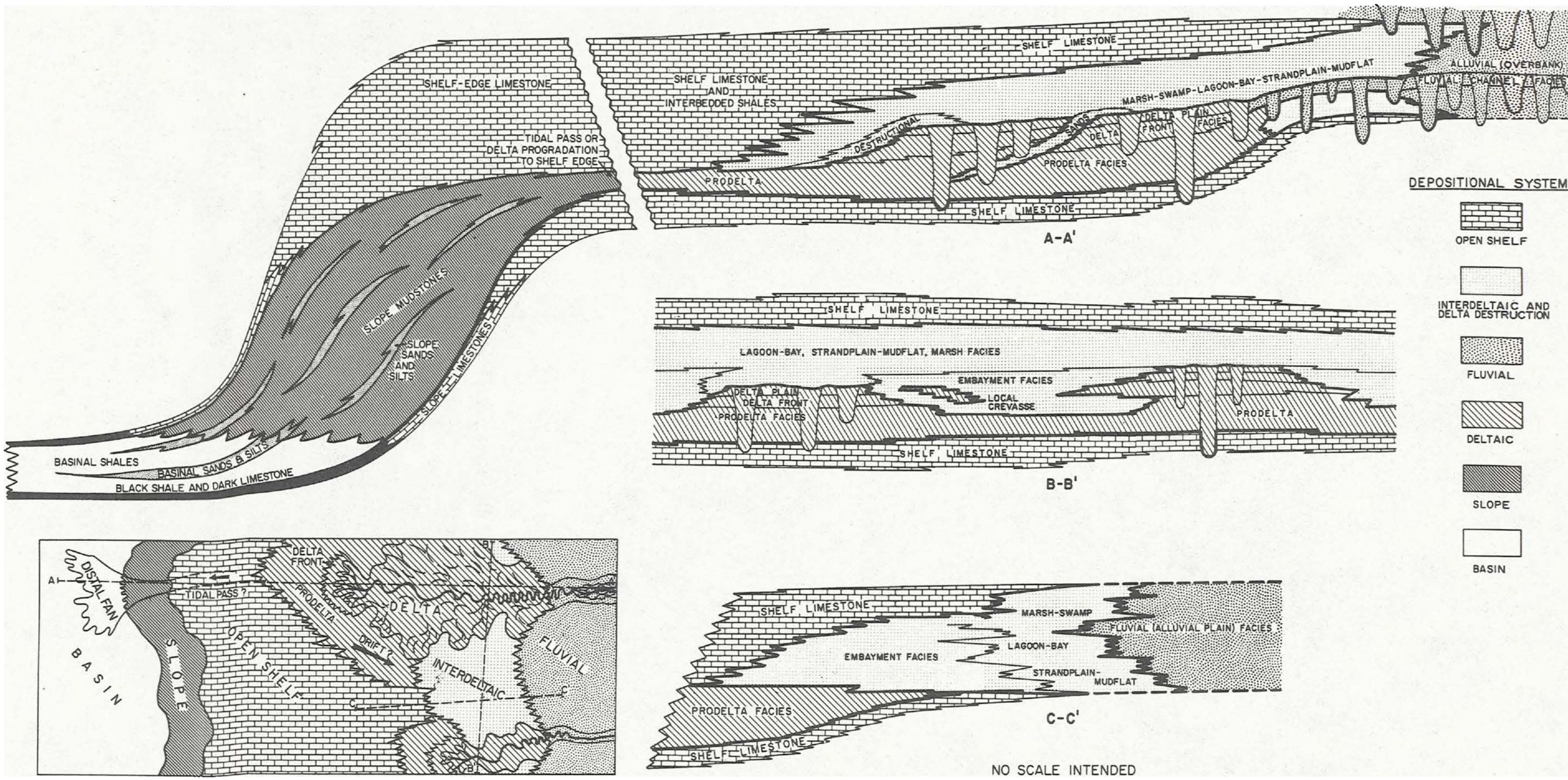

Figure 52. Schematic cross section along Cisco paleoslope showing principal depositional systems. Based on 15 cross sections and 13 net-sandstone maps. After Brown (1969d); reprinted with permission, Dallas Geological Society.

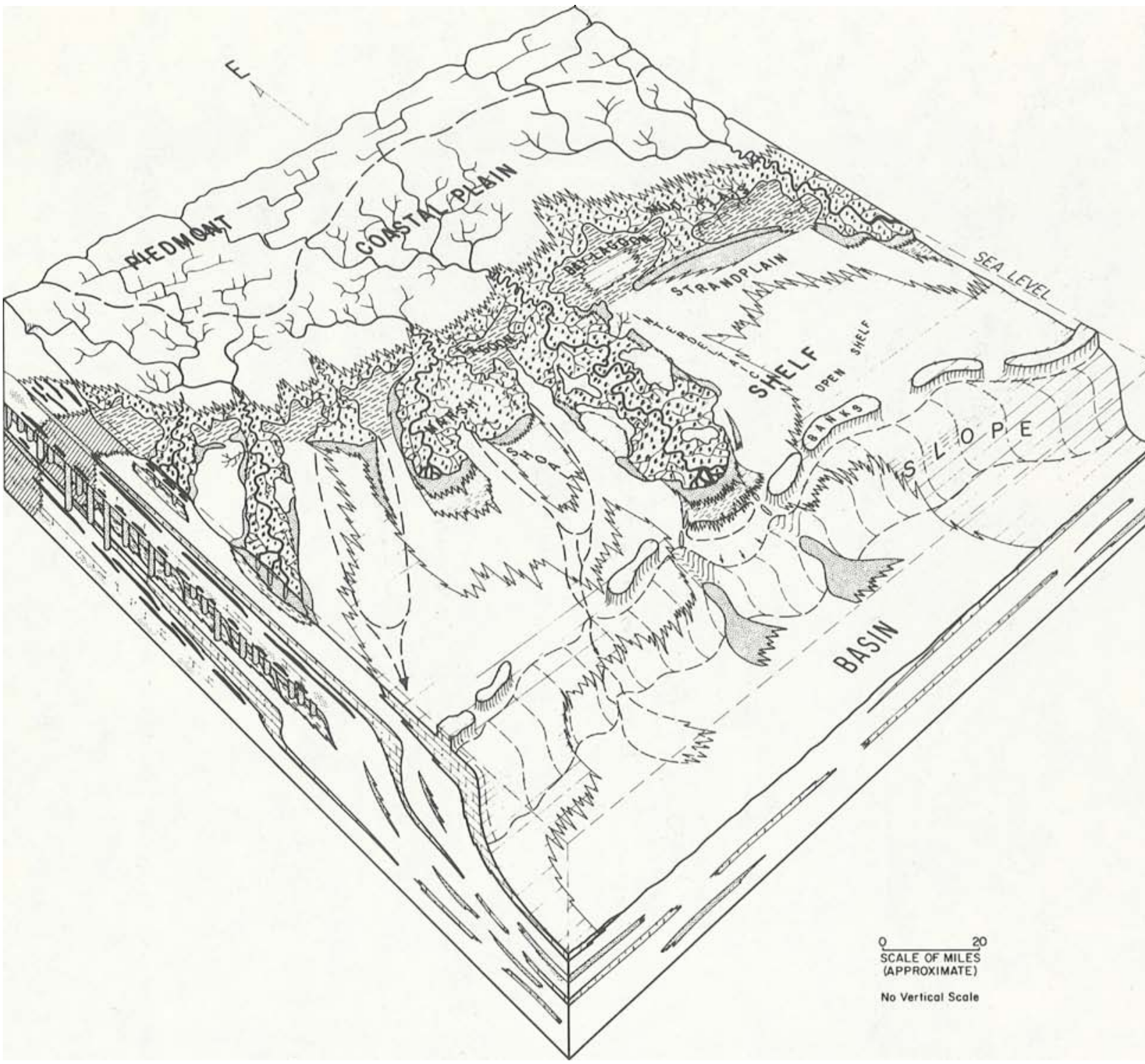

Figure 53. Block diagram, Cisco depositional systems illustrating shelf-slope relationship. After Brown (1969d); reprinted with permission, Dallas Geological Society.

represent periods of low terrigenous input to the slope and correlate with slope limestone aprons or limestone turbidites, as well as with the more widespread open-shelf limestones. These inferred shelf-to-basin stratigraphic markers provide the basis for regional correlation of fluvial-deltaic and slope-basin terrigenous clastic facies.

SUMMARY

Virgil and Wolfcamp facies were deposited in fluvial, deltaic, shelf, slope, and basinal depositional systems (fig. 52). Basin subsidence and sediment input accelerated during Virgil deposition as source areas were uplifted; by the end of Virgil deposition, the basin reached its maximum depth of at least 1,500 feet, and basinward progradation of thick, accreting slope wedges had reached a maximum. Subsidence decelerated and sediment supply diminished during Wolfcamp deposition; waning sediment supply indicates that source areas were becoming less elevated and stream paleogradients were decreasing. As terrigenous clastic input decreased, the volume of shelf-edge-bank carbonates increased until, by the end of Wolfcamp deposition, the region was principally an extensive carbonate shelf with landward tidal flats, sabkhas, and small deltas.

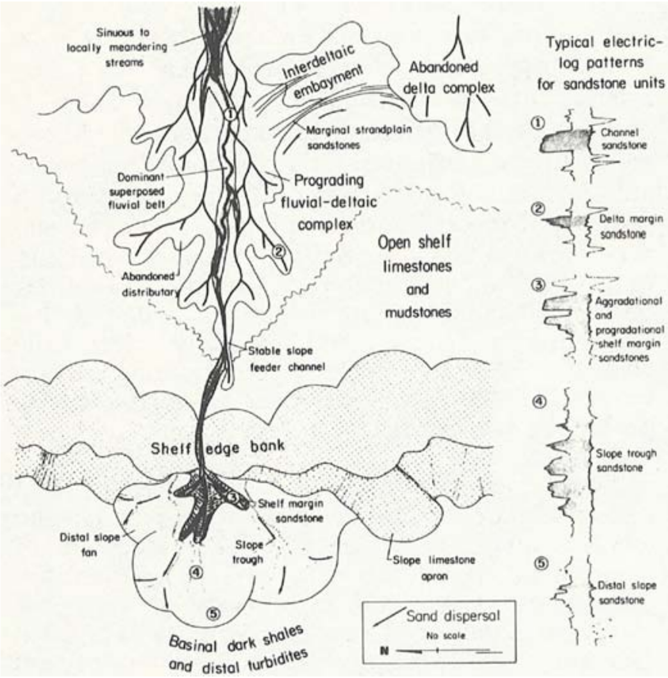

Figure 54. Sediment-dispersal system and principal depositional systems, Cisco Group, North-Central Texas. After Galloway and Brown (1972).

The Cisco fluvial-delta system was composed of braided, high- and low-sinuosity, meandering, and straight-distributary streams. The fluvial system supplied high-constructive delta systems; the fluvial-deltaic dispersal system shifted repeatedly up and down paleoslope in response to varying degrees of progradation and varying paleogradients (fig. 54). Interdeltaic embayments, supplied with sediments from the delta system, accreted basinward with delta-building, and sediments underwent marine reworking when deltas were abandoned. Each deltaic progradation and abandonment was followed by marine transgression over the compacting, subsiding clastic facies.

Shelf limestone was deposited in the absence of terrigenous sediment. Deltaic systems bypassed the Sylvester shelf-edge-bank system and supplied sediments to basinward-accreting Sweetwater slope wedges. Slope facies were deposited principally by turbidity flow to produce a slope facies tract from slope-margin sandstones to distal-slope turbidite fans. Sedimentation within the Midland Basin system was strictly pelitic and pelagic suspension deposition.

Approximately 75 percent of all Virgil and Wolfcamp terrigenous clastics ultimately were deposited within accreting slope wedges (fig. 54). Other deep cratonic basins with unusual stability and moderate to high sediment supply will probably exhibit similar lateral filling by slope systems rather than by deltaic systems.

FACIES INTERPRETATION: FIELD LOCALITIES

Proper analysis of facies and their subsequent integration into valid, genetic associations called *depositional systems* requires consideration of three-dimensional relationships of textures, sedimentary structures, fossils, stratigraphic relationships, and geometry of lithic units, among others. A total integration of all available data requires the use of information that can be uniquely derived from the subsurface (e.g., three-dimensional facies distribution and relationships, regional stratigraphic relations, sandstone body geometry and boundary relationships) and information that can best be observed in outcrop (e.g., petrography, textures, sedimentary structures, paleoecology, deformational structures, and others).

In previous sections of this guidebook, the integration of data derived from the subsurface and surface has been discussed and summarized for the Strawn, Canyon, and Cisco Groups. Modern depositional models and related stratigraphic documentation have been summarized and used to interpret and reconstruct the depositional framework for Middle and Upper Pennsylvanian rocks of North-Central Texas.

In this section, a wide and representative series of field examples will be presented, described, interpreted, and related to an inferred modern depositional model and depositional system. The purpose of this section is to provide field documentation to support interpretations presented in previous sections of the guidebook. Secondarily, it is hoped that by presenting field documentation, geologists will be able to evaluate the approach and criteria presently available for interpreting terrigenous clastic facies. Interpretations are based on the evaluation of these ancient facies in the light of present knowledge of depositional environments and sedimentary processes. Absolute modern analogs do not necessarily exist for all ancient facies, but by inferring process and environment from facies information, a genetic interpretation has been attempted.

We acknowledge that the state of the science of sedimentary rocks is changing significantly. Application of the growing volume of information on modern sediments is a subjective process; various workers may interpret the same fundamental data differently. Despite the subjectivity involved in reconstructing depositional conditions, the facies in North-Central Texas have been interpreted genetically and they have been integrated into a number of proposed depositional systems. Objective surface and subsurface data are presented so that the reader can evaluate and synthesize alternative interpretations. Every locality has been considered, not as an isolated outcrop, but in the context of the local and regional geologic framework. Interpretations are compatible with all available surface and subsurface data. Such an approach provides for prediction of facies character and three-dimensional distribution, which is an important goal in stratigraphy. As new knowledge becomes available, interpretations will be improved, sharpened, and possibly drastically changed. Failure to make interpretations on currently available data is, however, abdication of the geologist's obligation to interpret rocks and geologic history.

Twenty-six localities have been described from several hundred potential exposures; selection has involved presentation of as wide a spectrum of terrigenous clastic facies as possible within the constraints of accessibility, quality of exposure, and time limitations. Field examples have been grouped into fifteen localities and eleven optional localities (A-K). Visiting the fifteen localities will provide a fair representation of the terrigenous clastic facies exposed in the region; the optional localities provide the opportunity for a more intensive, but more time-consuming, look at facies variations and subtleties by the specialist.

The precise geographic location, stratigraphic position, regional and local geology, observed facies composition, and inferred depositional processes and environments are provided for each locality. Facies observed at each locality are tied to the regional distribution of the sequence in outcrop and subsurface. Outcrop sketches from photographic mosaics, as well as schematic drawings, are provided for each principal locality. Factual observations, as well as interpretive information, have been included on each locality illustration. In the discussion for each locality the reader is often referred to geologic maps, cross sections, and net-sandstone maps, as well as to models and vertical sequences. References cited supply detailed information on previous workers who have contributed ideas and concepts vital in understanding the genetic nature of this suite of sedimentary facies. It is anticipated that the geologist who visits these localities will be provided with sufficient facts to allow him to consider for himself the validity of the facies and process interpretations.

Principal responsibility for description and interpretation of field localities, including illustrations, is as follows: Localities 1, 2, A, 3, 4, B, C, F, and 8: A. W. Erxleben; Localities C, D, 5, 6, E, and 7: A. W. Cleaves; and Localities 9, 10, 11, G, H, I, J, 12, 13, 14, K, and 15: L. F. Brown, Jr.

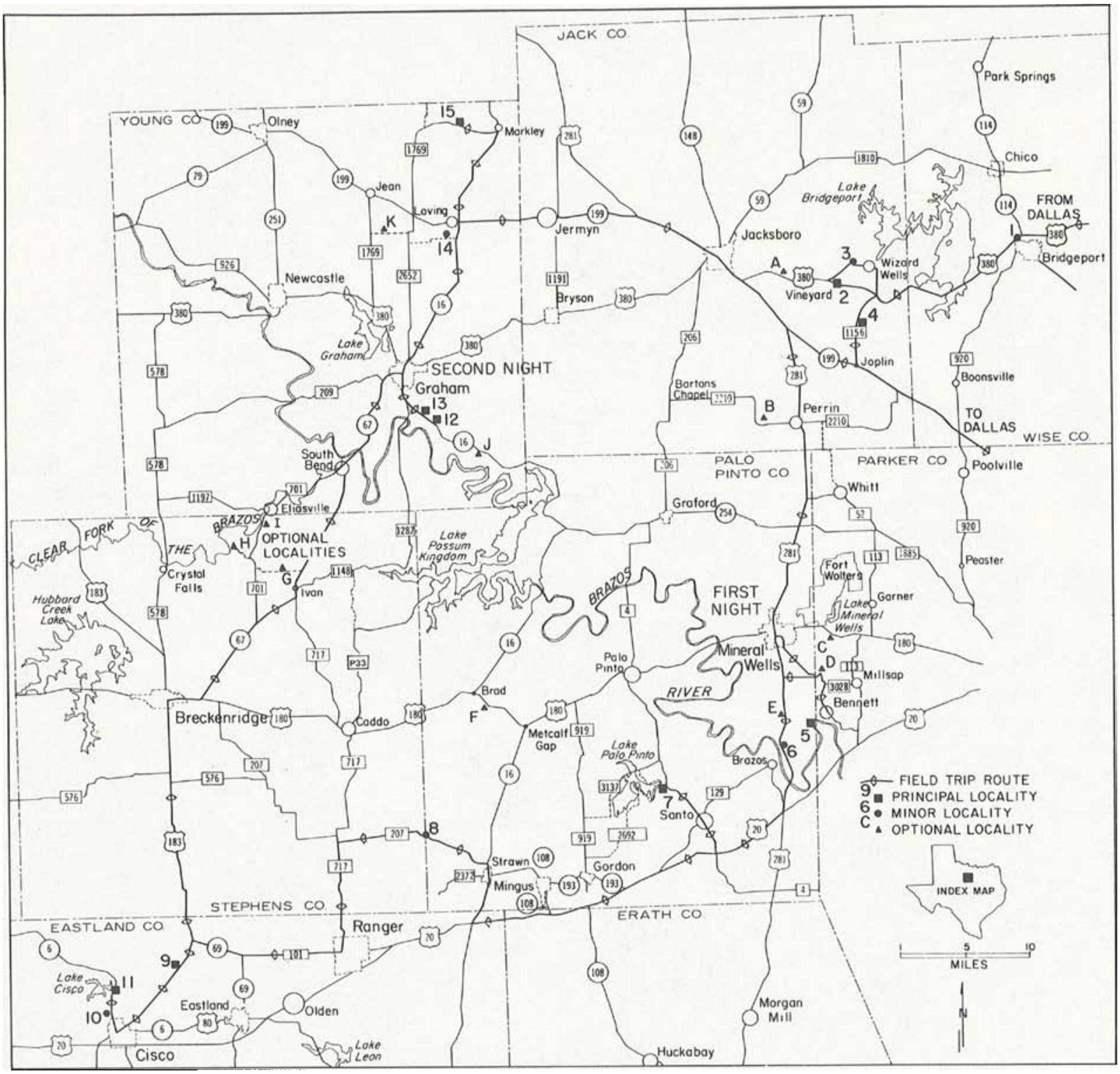

Figure 55. Field-locality map, Strawn, Canyon and Cisco Groups, North-Central Texas.

Locality 1: Slumped and Contorted Distal Delta-Front Sandstone Facies, Lake Bridgeport Shale

Significance and location.—Some of the most complexly deformed delta-front facies (fig. 57) in North-Central Texas occur at Locality 1, in road cuts on the west side of an underpass beneath the Chicago and Rock Island Railroad, along Texas Highway 380 (old 24) bypass, 0.3-mile west of its intersection with Texas Highway 14 at the northwest edge of Bridgeport, Wise County (figs. 55, 56). These distal delta-front sandstones (sandstone 1, fig. 56) of probable frontal-splay origin, are part of a deltaic lobe that prograded over prodelta facies in the lower part of the Lake Bridgeport Shale (fig. 56). Highly deformed flow rolls, injection features, and mass slumps illustrate the unstable character of oversteepened prodelta and delta-front slopes.

Local and regional stratigraphic setting.—The Lake Bridgeport Shale (=Wolf Mountain Shale) underlies the thick, isolated Chico Ridge carbonate bank (=Winchell Limestone) and the Rock Hill Limestone, a tongue of limestone debris washed from the bank early in its history (figs. 31, 56). The thick deltaic sandstone sequence within the Lake Bridgeport Shale (sandstone 1, fig. 56) prograded westward and southwestward over thin prodelta muds (lower part of Lake Bridgeport Shale). This delta lobe is part of the Perrin delta system (fig. 32), the principal depositional system

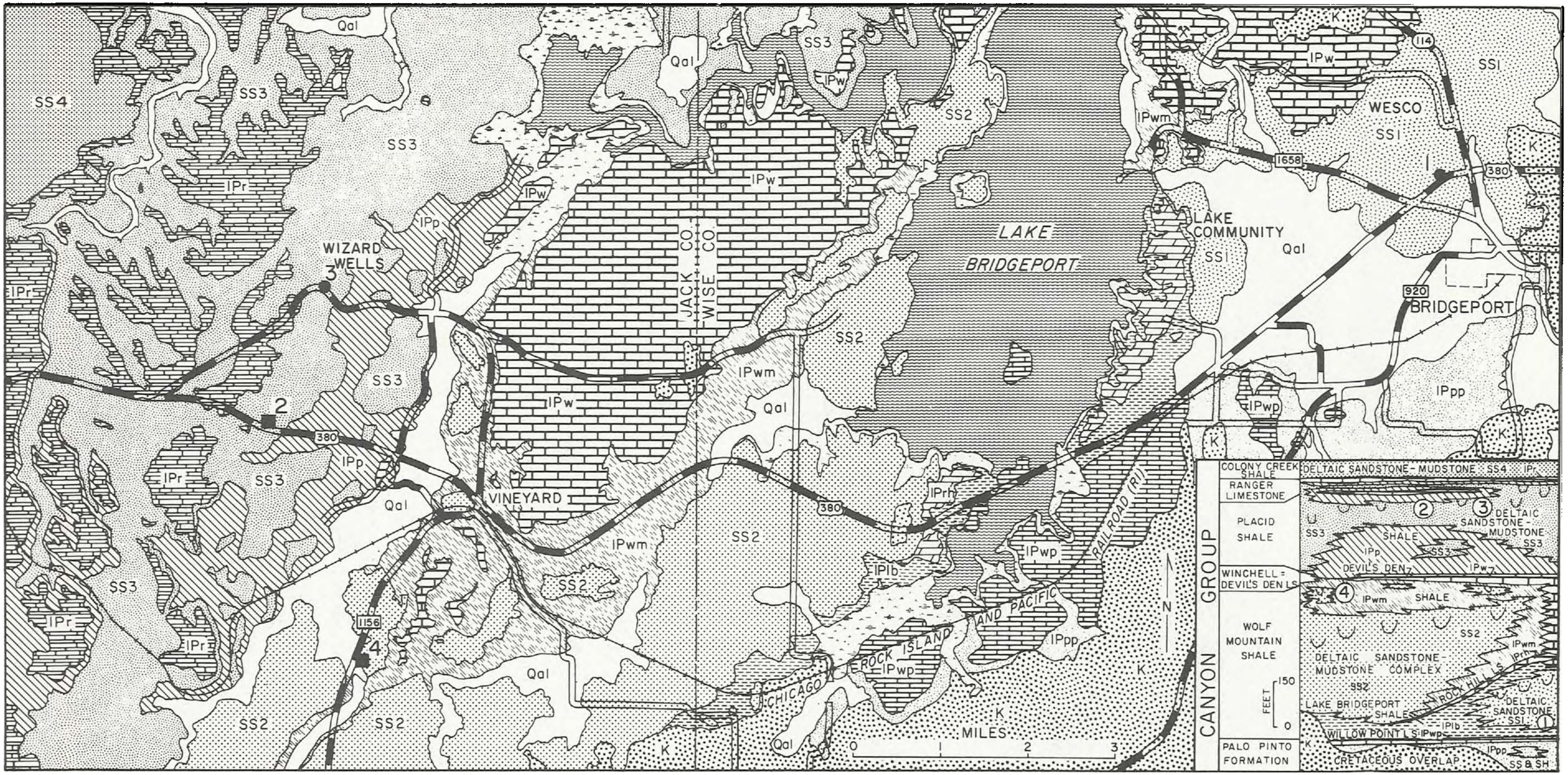

Figure 56. Geologic map, Canyon Group, Lake Bridgeport-Wizard Wells area, North-Central Texas. Mapping by A. W. Erxleben. Numbers refer to field localities.

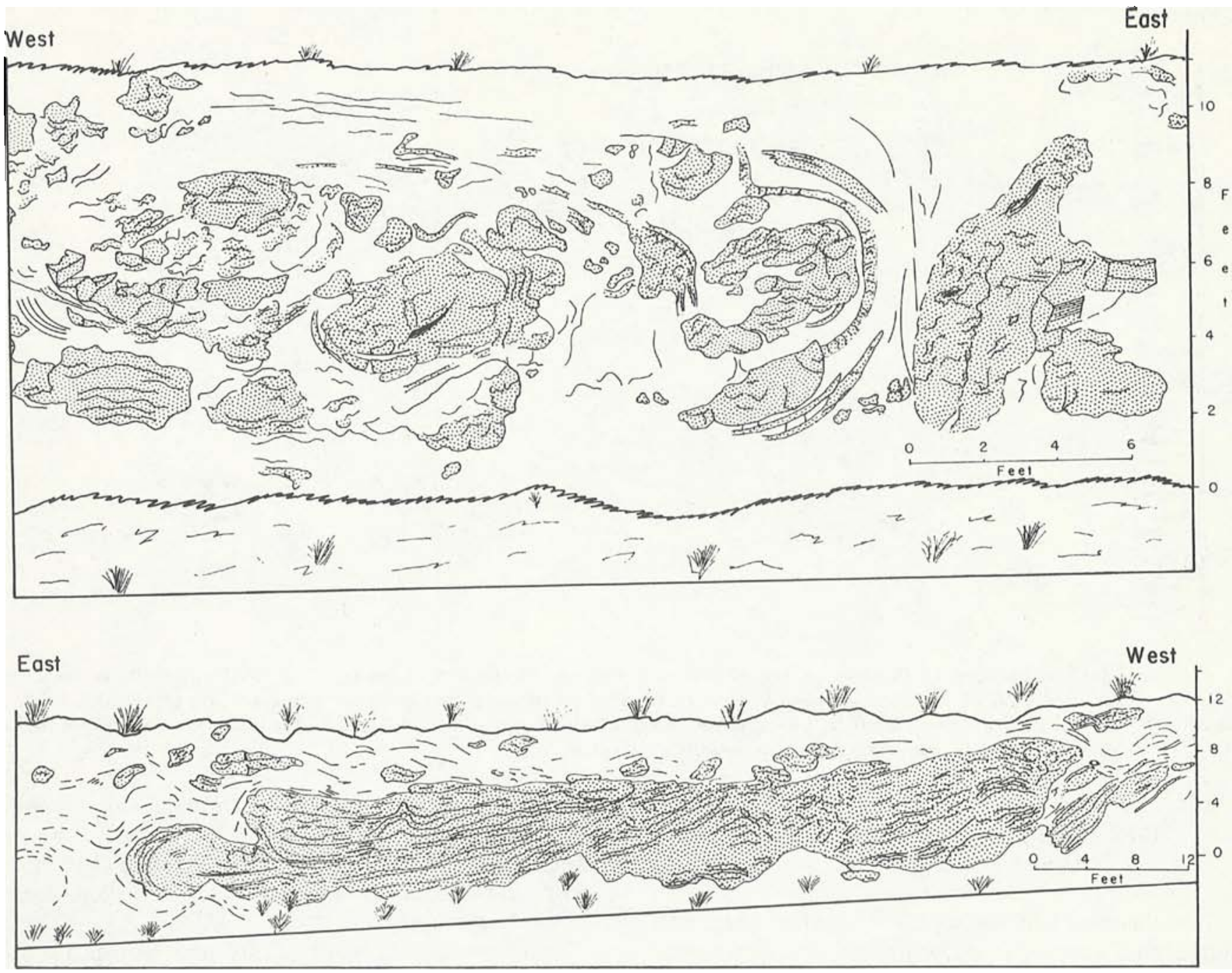

Figure 57. Field locality 1: Slumped and contorted delta-front sandstones, Lake Bridgeport Shale (lower part of Wolf Mountain Shale), U. S. Highway 380 near Bridgeport, Texas. See figs. 55, 56 for location. A. North side of highway. B. South side of highway.

in the region. Delta progradation of the Lake Bridgeport was over the Willow Point (=upper Palo Pinto) Limestone, a shallow-water marine facies.

The Perrin delta system during Wolf Mountain deposition prograded far to the west (fig. 35) between the thick Winchell (Possum Kingdom) and the Chico Ridge carbonate banks (fig. 34). Locality 1 is near the base of the Perrin system which regressed westward over Palo Pinto shelf carbonate facies (fig. 33). This delta-lobe complex, upon abandonment, provided a relatively stable platform on which the Chico Ridge carbonate bank developed.

Facies composition and inferred depositional processes.—Although regional delta progradation was westward, the sandstone at Locality 1 slumped eastward, probably from a point of failure on the eastern flank of a northwestward-building lobe. The sandstones are fine- to very fine-grained and contain plant debris. The prodelta mudstones are unfossiliferous, probably due to turbid water and rapid input of sediment.

Shallow-water carbonates above (Rock Hill Limestone) and below (Willow Point Limestone) preclude an excessively deep-water origin for the slumped sandstones.

Depositional summary.—During initial progradation of the Wolf Mountain interval of the Perrin delta system, gravity slides, slumps, and other soft-sediment, contemporaneous deformation affected oversteepened prodelta and delta-front slopes. Although common in such facies, deformed deltaic facies at Locality 1 are uniquely exposed and provide insight into the nature and degree that gravity-induced failure of sediment occurred within cratonic-basin delta systems.

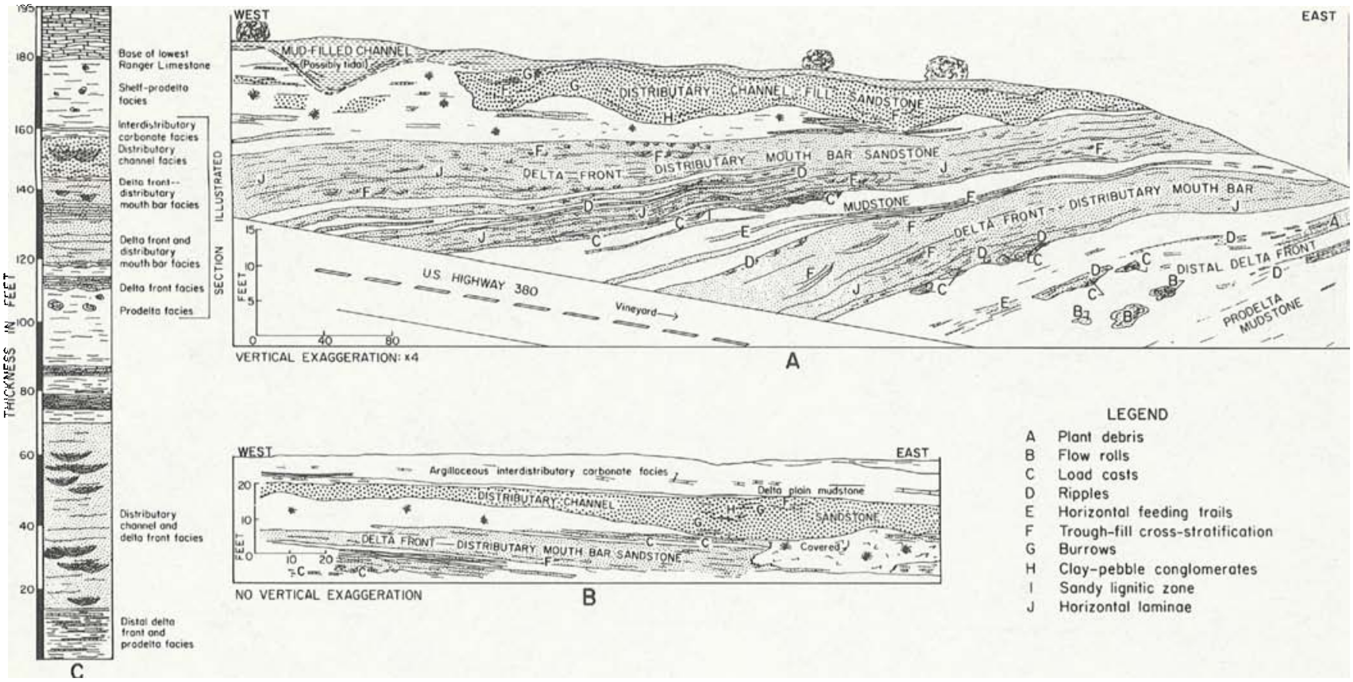

Figure 58. Field locality 2: Delta-front and distributary-channel facies, Placid Shale, U. S. Highway 380, eastern Jack County, Texas. See figs. 55, 56 for location. A. North side of road showing deltaic facies sequence in a small delta lobe. B. South side of road showing delta-front and superposed distributary-channel-fill sandstones. C. Measured section, upper part of Placid Shale exhibiting deltaic sequence and superposed transgressive facies.

Locality 2: Deltaic Facies Within A Minor Lobe of the Perrin Delta System, Uppermost Placid Shale

Significance and location.—An entire progradational and aggradational sequence within a minor delta lobe (fig. 58) provides a perspective of changing depositional processes and environments that occurred during deposition of 50 feet of mudstones and sandstones. Because of the nature of exposures in North-Central Texas, it is rare to observe, even in a minor lobe, a relatively complete deltaic sequence (fig. 39). Locality 2 is in a deep road cut along Texas Highway 380, about 2.5 miles west of Vineyard, Jack County, Texas (fig. 55, 56). Prodelta mudstones are overlain successively by two superposed channel-mouth-bar/delta-front sandstones and capped by distributary-channel-fill sandstones; a thin destructional sequence containing possible tidal facies rests on the deltaic facies.

Local and regional stratigraphic setting.—This Perrin sandstone and mudstone sequence occurs high in the Placid Shale (fig. 31). The sandstones (sandstone 3, fig. 56) support steep bluffs west of Wolf Mountain Shale valleys in the vicinity of Wizard Wells and Vineyard. The sandstones are overlapped by 20 feet of sandy, locally fossiliferous shale from another delta source; Ranger shelf limestones (fig. 38), which cap the sequence, crop out about 0.4-mile west of Locality 2 on Texas Highway 380.

Sandstones at Locality 2 are part of a principal delta-lobe complex of the Perrin system that prograded northwestward across the Eastern Shelf (fig. 37) during deposition of the Placid Formation. Deltaic sandstones extend far into the subsurface (figs. 33, 34). Some fluvial conglomeratic sandstones within sandstone 3 (fig. 56) occur along the outcrop, indicating that sufficient progradation occurred so that basinward-shifting alluvial plain environments reached the area of outcrop.

Facies composition and inferred depositional processes.—Prodelta facies exposed low in the road cut (fig. 58A) are laminated, dark gray to black, sandy and silty mudstones. Flow rolls and various isolated contorted sandstone bodies up to 6 feet in diameter occur within the uppermost (proximal) prodelta facies. Plant debris, including casts of *Calamites*, are found in the prodelta sequence; invertebrate fossils have not been observed in the mudstones.

Thin, distal delta-front sandstone beds occur near the top of the prodelta sequences. These units are plant-rich and rarely display wave ripples. Upward gradation from prodelta to deltaic sandstones is relatively abrupt; the two massive delta-front and channel-mouth-bar sandstone bodies display load structures on basal surfaces (fig. 58) and characteristics intermediate between high-constructive lobate and elongate deltas. Basal parts of each sandstone body exhibit load structures, but neither sandstone contains diapiric intrusions or highly deformed internal structures typical of bar-finger sandstones elsewhere in the Placid Shale. For example, about 10 miles north of Locality 2, 100 feet of massive, highly contorted bar-finger sandstone (figs. 17, 18) defines a principal high-constructive elongate delta lobe. At Locality 2, however, the basal beds of each deltaic sandstone are well-bedded delta-front facies, but more massive sandstone of channel-mouth-bar origin is superposed on the basal sandstone sheets. Although not bar-finger sandstones, these sandstones at Locality 2 likewise do not precisely resemble lobate delta-front sheet sandstones (fig. 20B).

Each delta-front/channel-mouth bar is about 15 feet thick and is composed of fine- to very fine-grained sandstone with many silty seams, plant debris, and some casts of *Calamites*. Horizontal laminations and small- to medium-scale trough cross-beds are dominant sedimentary structures. Wave-rippled bedforms are preserved on top of some beds. Locally, plant material is highly concentrated in thin sandy lignite seams. The base of the sandstones shows a variety of load casts. Both sand bodies thin eastward away from the lobe axis.

Poorly exposed sandy mudstone of probable delta-plain origin overlies the upper delta-front/channel-mouth bar, and is, in turn, cut by massive distributary-channel-fill sandstone (fig. 58A, B). The distributary channel is filled with medium- to coarse-grained sandstone and local zones of clay-chip conglomerate; vertical burrows that have been observed indicate periods of inactivity and bioturbation. Obscure large-scale trough cross-beds have been recognized in the channel fill. The channel cut downward from the delta-plain surface into the top of the subjacent channel-mouth bar (fig. 58B).

Following abandonment of the distributary channel, a thin veneer of delta-plain mudstone that covered the area was scoured by a symmetrical channel (fig. 58A). The channel may represent a tidal channel that developed on the delta platform after abandonment and during marine destruction. Another, better documented, tidal channel is exposed at Optional Locality F. The final event that is related genetically to the delta lobe at Locality 2 was deposition of a thin argillaceous biomicrudite (fig. 58B) packed with platy algal-mat and phylloid algal flakes; fossils include brachiopods, gastropods, and echinoid spines. The carbonate unit represents a subaqueous shoal that began to develop over the delta system.

Twenty feet of silty and sandy fossiliferous shale (fig. 58C) that was deposited over the delta at Locality 2 represents facies, which were strike-fed from another, slightly younger lobe nearby.

Depositional summary.—Perrin deltas prograded northwestward (fig. 37) during deposition of the Placid Formation. A minor lobe prograded northwestward through the vicinity of Locality 2. Only the prodelta and delta-front/channel-mouth-bar environments reached Locality 2; a second lobe with thin prodelta facies later built across the initial lobe and extended some distance northwest of Locality 2. A channel of the distributary system that fed the lobe cut into the underlying channel-mouth bar. A marine shoal developed on the delta as it subsided following abandonment.

This small lobe of the Perrin delta system does not display growth faulting or excessive compactional deformation. It represents a high-constructive delta that exhibits facies and geometry that are intermediate between elongate and lobate types (fig. 20).

Optional Locality A: Highly Deformed Distributary-Channel-Fill and Bar-Crest Facies, Colony Creek Shale

Distal distributary-channel-fill facies superimposed on growth-faulted channel-mouth-bar-crest facies are well displayed in a sandstone within the Colony Creek Formation (fig. 31, 61). Locality A is located along Texas Highway 380, 5.2 miles west of Locality 2 and 2.7 miles east of its intersection with U.S. Highway 281, east of Jacksboro, Jack County, Texas (fig. 55). Sandstones exposed at Locality A occur between the Ranger and Home Creek Limestones throughout much of the Colony Creek outcrop in Jack County. These facies extend basinward to the northwest, across the Eastern Shelf as a series of progradational delta lobes (fig. 61B).

This locality resembles Locality 3; channel-mouth-bar-crest facies are cut by shifting distal distributary channels. Horizontal laminations with numerous trough cross-beds are the most common sedimentary structures; some ripple cross-

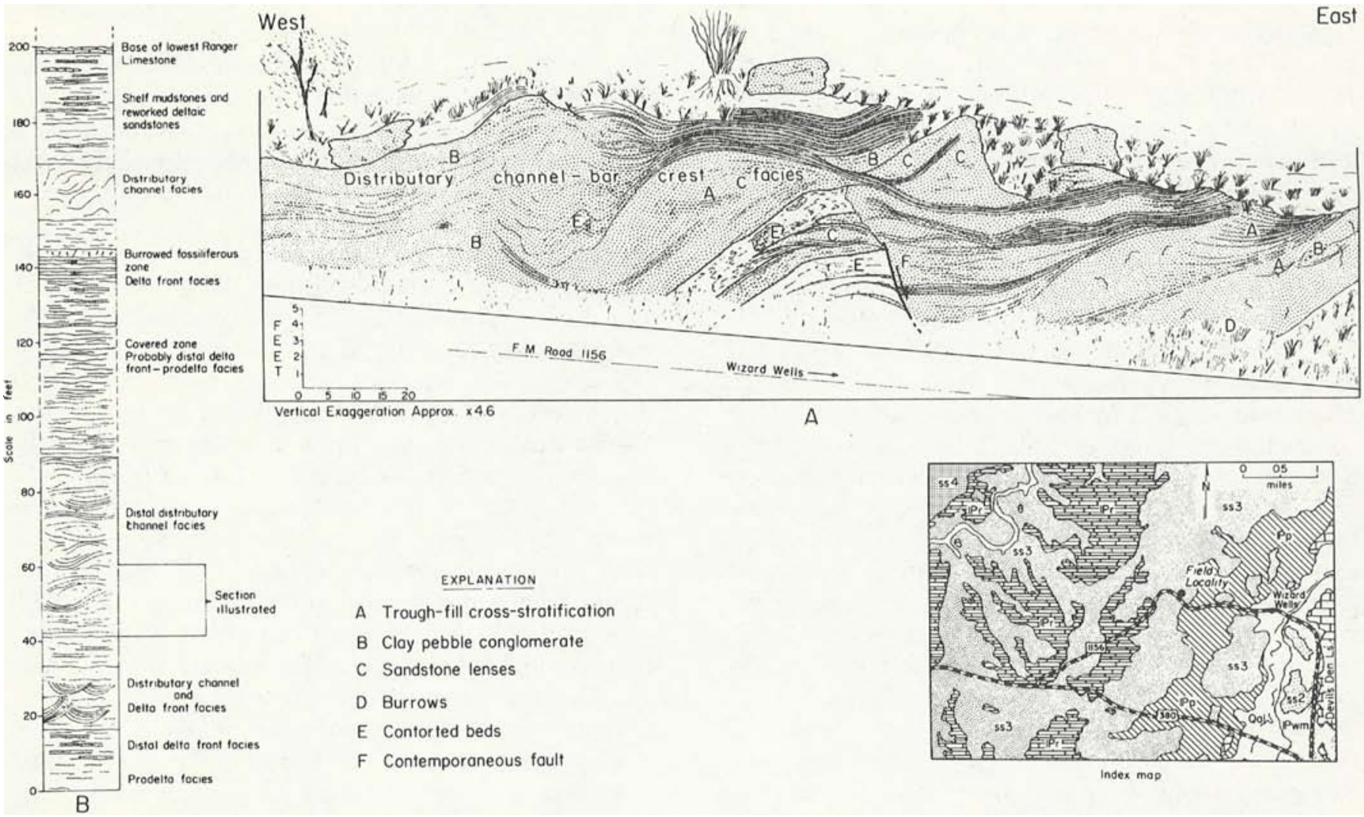

Figure 59. Field locality 3: Distal distributary-channel and bar-crest facies, upper part of Placid Shale, Farm Road 1156, eastern Jack County. See figs. 55, 56 for location. A. Complex distributary-channel-fill deposits displaying compactional features. B. Measured section, upper part of Placid Shale.

laminations were observed. Several faults were active during deposition.

The exposed sandstone unit at Locality A probably reflects intermittent high flow-regime conditions over the bar crest, cut locally by scour channels during peak discharge. Scour channels probably shifted as the thalweg of the distributary shifted. Trough cross-beds and ripple cross-laminations indicate lower flow regime, either during waning discharge, or at a site lower on the bar in deeper water, or laterally to the scour-channel axis near subaqueous levees. Sedimentation on the bar initiated faults that grew intermittently as loading reached critical limits. Horstlike blocks suggest incipient mud-lump development (fig. 18).

The fine-grained sandstone facies contains local occurrences of clay chips and plant debris. A mud-filled channel cuts the sandstone. Locality A is situated near the base of a thick sequence of Perrin delta facies deposited in the Colony Creek Formation.

Locality 3: Highly Deformed Distal Distributary-Channel/Bar-Crest Facies, Placid Shale

Significance and location.—The basal 20 feet of a superposed stack of distributary-channel-fill and bar-crest deposits exhibits compactionally deformed and contemporaneously faulted sandstones (fig. 59). The sandstones are inferred to represent the transition from distal distributary channel to channel-mouth-bar crest. The shifting thalweg developed complex internal geometry; rapid deposition overloaded thin, subjacent, water-saturated mudstones and initiated contemporaneous faulting. Reoccupation of the channel system resulted in deposition of 50 feet of superposed channel units.

Locality 3 is on the north side of Farm Road 1156, about 1.4 miles west of Wizard Wells, Jack County, Texas (figs. 55, 56); this exposure provides insight into the internal geometry and composition of a distal segment of a principal distributary-channel system.

Local and regional stratigraphic setting.—Locality 3 is situated within the same deltaic sandstone and mudstone sequence (sandstone 3, fig. 56) observed at Locality 2, but Locality 3 is much lower in the Placid sandstone and mudstone unit. Correlation of facies between Localities 2 and 3 can be accomplished by comparing measured sections (figs. 58C, 59B). Localities 2 and 3 are within a Placid delta complex (fig. 31) that extends northwestward into the subsurface (figs. 33, 34, 37).

Facies composition and inferred depositional processes.—Distributary-channel-fill and bar-crest sandstones are fine- to medium-grained and well sorted, but they contain some localized zones of clay-chip conglomerate. Horizontal feeding trails and burrows occur locally near the base of the sandstone; burrowing of this sort indicates periods of low discharge or temporary channel abandonment. High discharge is indicated by the very large scour channels and the dominance of horizontal laminations over trough cross-beds. Shallow flow within the channels cutting the channel-mouth bar during peak discharge probably reached high flow regime.

The most obvious feature displayed at this locality is the shift in flow, first to the east (right) and then back to the west (left). Overloading along these two thalweg positions may have been responsible for localized subsidence along the two channel axes; a shale horst block in the center of the exposure points to this differential loading and incipient shale diapiric intrusion. Two inferred thalweg positions in distal distributaries are compatible with modern examples where middle-ground or median sand bars accumulate, leading to the distinctive bifurcation of distributary channel flow. Faulting was contemporaneous, as it dies out upward.

Superposed distributary sandstone (westward along Farm Road 1156) is somewhat coarser. One fossiliferous burrowed zone contains fusulinids, crinoid fragments, broken mollusk shells, and orthocone nautiloids; such occurrences record channel abandonment. As it is inconceivable that a single Canyon distributary stream could deposit 50 feet of sand, these thick channel-fill sandstones represent several superposed channel-fill units deposited as the sand body slowly subsided.

Depositional summary.—Locality 3 was the site of relatively permanent distributary streams during deposition of the upper part of the Placid Shale. These distributaries are elements of a principal lobe of the Perrin delta system that prograded northwestward 40 to 50 miles across the Eastern Shelf (fig. 37). Once established by an initial delta progradation across the area (fig. 59B), distributaries repeatedly reoccupied the channel courses, depositing thick channel-fill sandstones. It is inferred that the transition from distal distributary to channel-mouth-bar crest is exposed at Locality 3. Switching thalwegs allowed the distributary stream to cut the bar crest repeatedly. High flow conditions would be compatible with water moving through shallow channels under peak discharge. Compactional deformation of the sandstones with incipient mud lumps is to be expected within distal-distributary to channel-mouth-bar-crest facies.

Locality 4: Distributary-Channel and Marine Destructional-Transgressive Facies, Uppermost Wolf Mountain Shale

Significance and location.—A small delta lobe in the upper part of the Wolf Mountain Shale (fig. 60) provides facies documentation of marine destructional-transgressive environments and processes. Within a small area on the Yates Ranch, a complete section (fig. 60B) showing the vertical shift in depositional environments can be traversed. Locality 4 is at a low road cut on the east side of Farm Road 1156 and continues for 0.5-mile east of the road on the Yates Ranch, about 2.5 miles southwest of its intersection with Texas Highway 380, Jack County, Texas (fig. 55, 56). The Yates Ranch *absolutely must not* be entered without prior permission from the owner, Mr. B. Jones; ranch headquarters is 0.4-mile southeast of Vineyard on a graded county road south of the Chicago-Rock Island Railroad. The nature of marine reworking, bioturbation, and eventual transgression of a shelf limestone environment occurs within about 50 feet of section.

Local and regional stratigraphic setting.—Locality 4 is situated in a small delta lobe (part of sandstone 2, fig. 56) high in the Wolf Mountain Shale. The Devil's Den Limestone (=Winchell Limestone), a tongue of limestone extending southwestward from the crest of the Chico Ridge, caps outliers of the uppermost Wolf Mountain Formation east of Farm Road 1156 (fig. 56). A broad dipslope of the Devil's Den Limestone crops out northeast of Vineyard; this limestone tongue pinches out southwestward onto the delta platform precisely at Locality 4.

The deltaic sandstones and mudstones at Locality 4 (sandstone 2, fig. 56) are part of a large

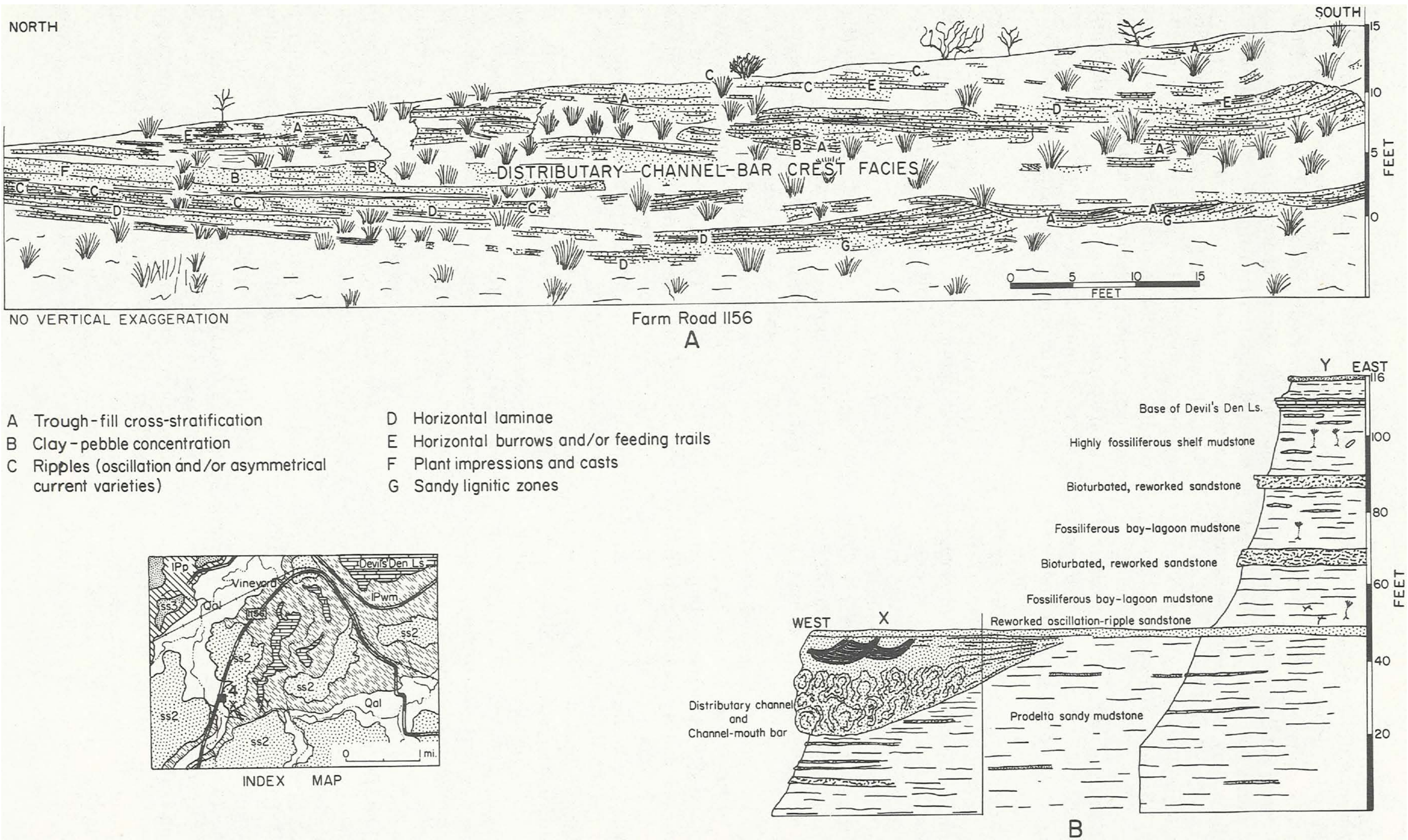

Figure 60. Field locality 4: Deltaic, delta-destructional and marine-transgressive facies, upper part of Wolf Mountain Shale along Farm Road 1156 near Vineyard, eastern Jack County, Texas. See figs. 55, 56 and index map for location. A. Distributary-channel/bar-crest facies in east road cut. B. Measured sections X and Y, Yates Ranch, east of road cut showing marine-destructional and transgressive facies; see index map for locations.

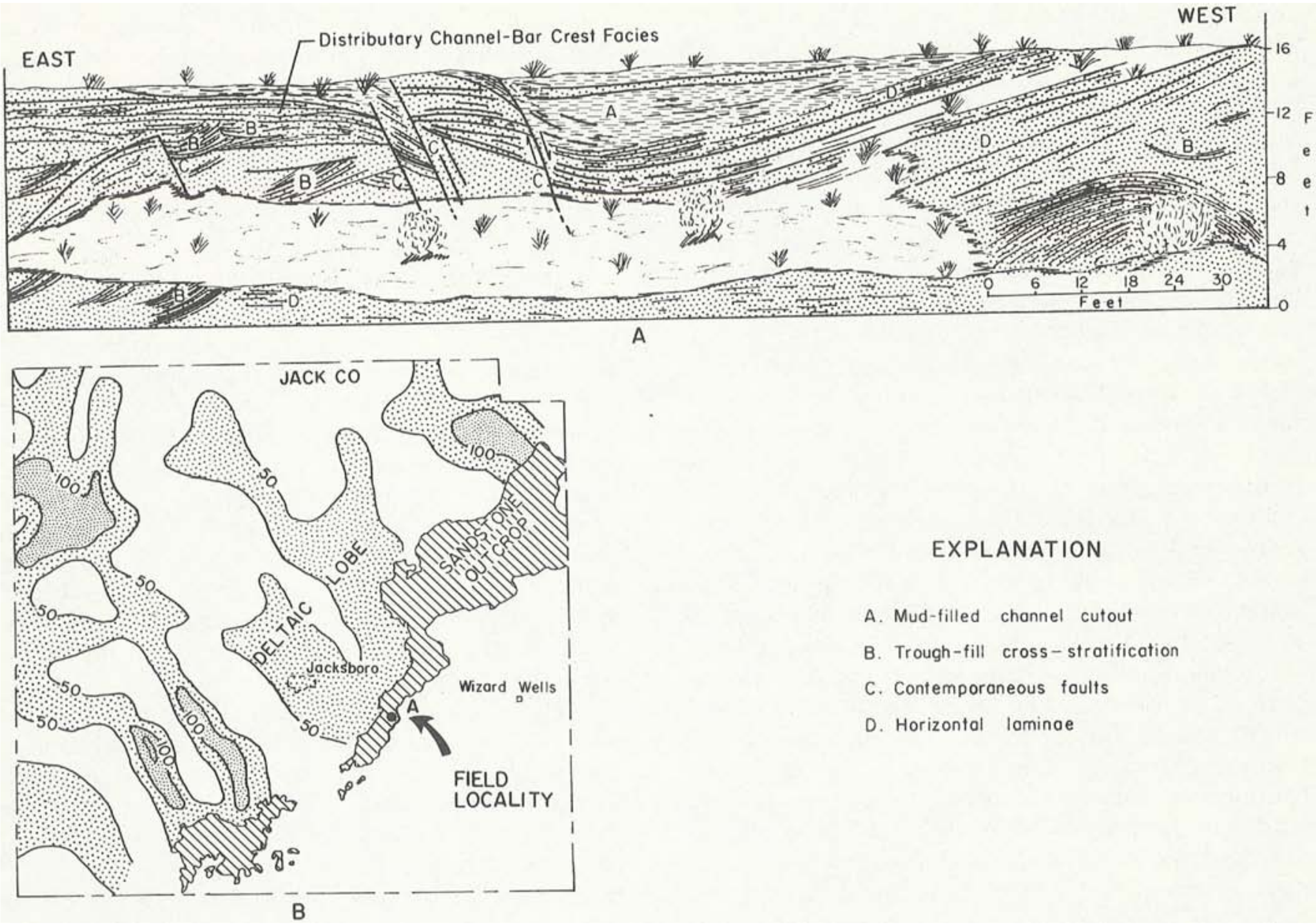

Figure 61. Field locality A (optional): Distributary-channel-fill facies, Colony Creek Shale, north side of U. S. Highway 380, east of Jacksboro, Texas. See figs. 55, 56 for location. A. Distributary-channel-fill facies showing compactional features and mud-filled channel. B. Net-sandstone map of Colony Creek Shale showing Locality A.

deltaic complex of the Perrin system that extends many miles across the Eastern Shelf (figs. 33, 34, 35). The delta lobe at Locality 4 is one of the last deposited during Wolf Mountain progradation; the Devil's Den and uppermost Winchell Limestones transgressed the abandoned delta facies, but did not succeed in overlapping the entire delta platform. Locality 4 is at the pinch-out or shoal line of the Winchell—Devil's Den shelf facies.

Facies composition and inferred depositional processes.—The road cut exposes distal distributary-channel-bar-crest sandstones that are thin bedded and fine- to very fine-grained. This unit is part of a high-constructive elongate delta system (fig. 17). Horizontal laminations fill broad scour troughs cut into the bar-crest facies. The sandstones contain abundant plant debris and locally a sandy lignite seam. The broad shallow troughs contain lenses of clay-chip conglomerate. Trough cross-beds, wave-rippled beds, and ripple cross-laminations occur within the facies. Horizontal burrows and feeding trails locally occur within the sandstone body, indicating temporary abandonment during which time the distal deltaic environments were occupied by marine invertebrates. The sandstone body rests on laminated mudstone (not exposed in the road cut) containing large flow rolls and highly contorted sand-injection structures. This sequence of prodelta and distributary-channel/channel-mouth-bar facies composes a small, high-constructive elongate delta lobe (fig. 20A) that overlies thick deltaic facies of the middle Wolf Mountain Formation.

About 0.3-mile east of Farm Road 1156 at measured section X (fig. 60B), 20 feet of channel-mouth-bar sandstone is overlain by about 10 feet of distributary-channel-fill facies approximately equivalent to the sandstone in the nearby road cut. The channel-mouth-bar facies is a massive, fine-grained sandstone with a convex downward shape; it is highly deformed by soft-sediment compaction. Superposed on the channel-mouth bar is about 10 feet of trough cross-bedded distributary channel-fill facies best exposed in the road cut to the west.

The sand body at measured section X is a thin, narrow, bar-finger sandstone that trends approximately east-west parallel to paleoslope. Beneath the elongate sandstone body is 40 to 60 feet of sandy and silty prodelta mudstone. The prodelta facies is unfossiliferous and contains thin, fine- to very fine-grained sandstone beds of distal delta-front or proximal prodelta origin that were frontally splayed onto the prodelta slope.

Eastward the bar-finger sandstone pinches out within a few hundred feet; only a thin, destructional, highly burrowed and wave-rippled sheet sandstone extends eastward 0.25-mile from section X to section Y (fig. 60B). The thin destructional sandstone represents marine reworking and redistribution of deltaic sand after abandonment and subsidence of the delta lobe. Approximately 50 feet of extremely fossiliferous sandy mudstone contains intensively burrowed, vuggy, fine-grained sandstone beds up to 5 feet thick; the beds contain the brackish-water pelecypod *Myalina* and abundant vertical- and horizontal-branching burrows. Local small-scale trough cross-beds near the top of the sandstone beds demonstrate the marine energy level on this abandoned delta shoal. These units are analogous genetically (but not in scale) to transgressive sheet sands and thin delta-destructional islands of the Chandeleur Sound overlying the delta plain of the foundered St. Bernard lobate delta of the Holocene Mississippi delta. Increasingly fossiliferous, calcareous shelf mudstones that overlie the destructional sandstones grade upward into the Devil's Den shelf limestone. Invertebrates present include sponges, crinoids, bryozoans, a variety of productid and spiriferid brachiopods, orthoconical nautiloids, and nuculid pelecypods. The Devil's Den shelf facies is a phylloid algal biomicrudite and biosparite.

Depositional summary.—Final delta-building in the Wolf Mountain Formation occurred in the vicinity of Locality 4. Deltas prograded northwestward beyond the outcrop; bar-finger sandstones composed of superposed channel-mouth bars and distributary-channel fill subsided into subjacent mudstones, resulting in highly deformed bar facies. Distributary-channel facies at Locality 4 represent distal channel scour of bar-crest facies under high flow regime. Upon delta abandonment, marine reworking and bioturbation developed thin destructional sheet sandstones and barlike shoals. Continued subsidence led to marine shelf environments represented by fossiliferous, calcareous shale and limestone (Devil's Den Limestone).

Optional Locality B: Superposed Channel-Mouth-Bar/Distributary-Channel-Fill (Bar-finger) Facies, Wolf Mountain Shale

A bar-finger sandstone body approximately 50 feet thick exhibits contemporaneous and post-depositional deformation. Locality B is situated along and north of Farm Road 2110, 2.9 miles west of its intersection with U. S. Highway 281 (Perrin), Jack County, Texas (figs. 31, 55). The sandstone underlies the Winchell Limestone and occurs above the Oran Sandstone (fig. 31). The deltaic sequence is a minor lobe of the Perrin system that built northwestward across the Eastern Shelf during deposition of the Wolf Mountain Formation (figs. 34, 35).

Sixty feet of sandy and silty mudstone is overlain by about 50 feet of massive channel-mouth-bar and superposed distributary-channel-fill sandstones (fig. 20A). The massive sandstone is well exposed north of the highway (private property) where large-scale trough cross-beds overlie massive, deformed sandstones. Plant debris is common in the facies. The entire sandstone body appears to have rotated 20 to 30 degrees to the south. The internal character of the unit can be observed on the faces of massive, automobile-sized blocks.

Adjacent to Farm Road 2110, a thin-bedded delta-front sequence has slumped downslope into underlying prodelta mudstones along a well-defined glide plane; this motion possibly occurred during deposition rather than during modern times.

Optional Localities C, D, and E: Brazos River Sandstone Facies Mosaic

Locality C: Roadside park 7.1 miles south of Mineral Wells on east side of U. S. Highway 281 (figs. 55, 62). Tables are set on hill slope adjacent to large blocks of fluvial Brazos River Conglomerate.

Locality D: Road cut 5.6 miles east of Mineral Wells on Farm Road 3027, just southwest of Mineral Wells airport (figs. 55, 62). All facies of Brazos River Sandstone are represented.

Locality E: Road cuts 5.4 miles east from center of Mineral Wells on U. S. Highway 180 (figs. 55, 62). Cut adjacent to eastbound lane is slightly lower in the section and shows the relationship between the lowest Brazos River and the underlying Mingus Formations. Only delta-front facies are present at this locality in the Brazos River.

Significance and location.—The distal prodelta facies of the uppermost Mingus Formation is overlain by thin-bedded, flaggy, delta-front sandstone of the Brazos River Sandstone. In the northern part of its outcrop belt, the delta-front sandstone is separated from an overlying fluvial conglomerate by an interdistributary-bay shale containing a detrital coal unit (fig. 24). The fluvial unit contains both well-preserved small channels at the base and a large-scale trough-cross-bedded blanket of conglomerate at the top.

These three optional localities are significant because they demonstrate the variety of facies in the Brazos River Formation. A notably scenic area is where the Brazos River cuts across the outcrop belt of the Brazos River Sandstone, forming steep bluffs and slopes with up to 200 feet of relief. In southwestern Palo Pinto County, the fluvial facies grades into strike-oriented, shallow-marine, carbonate-cemented sandstone.

Local and regional stratigraphic setting.—The Brazos River Sandstone crops out as a significant ridge-forming element from eastern Eastland County to west-central Parker County where it disappears beneath Cretaceous cover (fig. 62). In its northern outcrop area near Mineral Wells, the unit is exposed just updip from a major deltaic lobe (fig. 29); surface evidence substantiates trends of subsurface isolith contours. Studies of paleocurrent orientation for the large-scale cross-beds in the area between Mineral Wells and Palo Pinto indicate flow to the NNW and a local source to the southeast (Briggs, 1960). Along strike, the Brazos River Formation attains a maximum thickness of greater than 100 feet of sandstone and conglomerate near Locality C, but thins northeastward to 60 feet at Locality D and to less than 40 feet (and contains only sandstone) at Locality E. A similar thinning takes place to the southwest, as the total thickness of sandstone and conglomerate is 80 feet at the Lake Palo Pinto spillway and 30 feet (no conglomerate) near Thurber. Again, from the net-sand map (fig. 29), it can be seen that the main delta was concentrated in what is now the shallow subsurface of western Jack and Young Counties.

Thicknesses cited in the previous paragraph are directly reflected by the facies composition of the Brazos River Formation. At the roadside park (Locality C), the sandstone-conglomerate thickness is maximum, and the fluvial facies alone is more than 40 feet thick. Near the Mineral Wells airport the fluvial facies is 25 feet thick, and east of Mineral Wells only the delta-front facies crops out.

Facies composition and inferred depositional processes.—At all localities observed, the contact between the Mingus Shale and the lower, delta-front facies of the Brazos River Formation is an abrupt one. No coarsening-upward sequence, like that described for the prodelta sequence at the Bennett delta lobe (Locality 5) is observed at any of the outcrops. The delta-front sandstone unit is thin and flaggy throughout; symmetrical (oscillation) ripples occur on the surfaces of many of the flags. Small-scale trough cross-beds and rare zones of planar bedding are the most prominent internal sedimentary structures. Ripple-drift cross-laminations are quite common in the delta-front facies at the Lake Palo Pinto spillway (fig. 65B). Low-angle large-scale trough cross-beds occur in the road cut of the westbound lane (U. S. Highway 180) at Locality E. The delta-front sandstones have been reworked by marine processes to the extent that a distinct channel-mouth bar is virtually absent from any of the described sections. Inasmuch as the three optional localities (C, D, E) and the Lake Palo Pinto measured section (fig. 65B) form a line of sections cutting across the net-sand-isolith maximum, the absence of a discrete channel-mouth-bar facies suggests that the delta-front sheet sands of this high-constructive lobate delta constitute virtually all of the delta-front facies. Small channel-mouth bars apparently formed only at the point of debouchment for individual distributaries.

At Locality D, the fluvial conglomerate and the delta-front sandstone are separated by an interdistributary-bay shale. The shale unit contains a thin zone of detrital lignite and a very sparse fauna of bivalves, crinoid detritus, gastropods, and brachiopods. To the south, this shale facies is lost and is replaced by a thicker delta-front sequence.

The fluvial conglomerate facies at the top of the Brazos River Formation is best observed in the roadside park (Locality C) and in an abandoned quarry across the highway from the park. Very large-scale trough cross-beds, some with basal scours up to 10 feet long, and tabular cross-beds are the only sedimentary structures present in the conglomeratic unit. The conglomerate is a chert

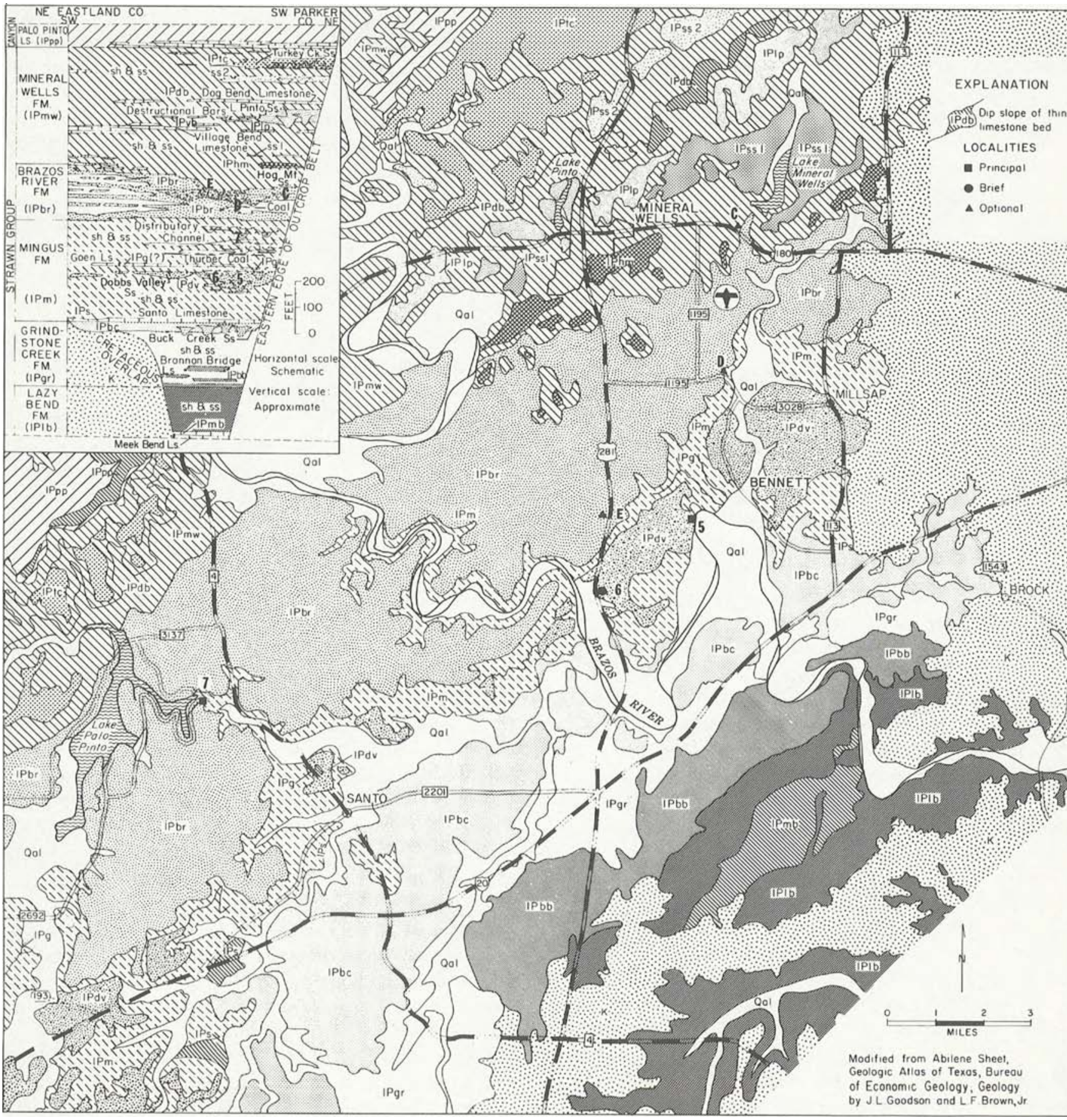

Figure 62. Geologic map, Strawn Group, Mineral Wells area, North-Central Texas. Adapted from Abilene Sheet, Texas Geologic Atlas (1972). Numbers refer to field localities.

arenite, with the largest chert clasts exceeding 60 mm in diameter. The vertical sequence of sedimentary structures (fig. 15A) suggests a braided stream complex, although it seems unlikely that such a system should be laid down directly on top of a delta; meandering streams (like the one described as a part of the delta-plain facies at the Lake Palo Pinto spillway) would be a much more logical expectation. It is possible that the coarse-grained fluvial unit is part of an incised valley-fill fluvial system that formed in response to changes in local base level (fig. 14). It can be seen from the net-sand map (fig. 29) that the outcropping Brazos River delta system is linked to a thick sand trend that progaded 20 or more miles to the west and northwest. The top part of this trend contains the thick valley-fill gravels. Perhaps avulsion of a major distributary far downdip would provide a significant increase in stream gradient and even cause 30 to 50 feet of incision of a narrowly confined, high-gradient fluvial system into the lower delta-front facies of the Brazos River Formation.

Locality 5: Growth-Faulted Delta-Front Sequence, Dobbs Valley Sandstone

Significance and location.—The distal prodelta facies of the lowest Mingus Shale is overlain by the complete vertical sequence of sandstone facies characteristic of a small delta lobe (fig. 63). The most prominent units include a proximal-prodelta facies containing flow rolls and slumped fragments from the delta front; a thin-bedded, growth-faulted delta-front sandstone unit; and a relatively undeformed, massive channel-mouth-bar facies.

Locality 5 involves two railroad cuts on the main line of the Texas Pacific Railroad just west of Bennett, Parker County (figs. 55, 62). The more distant of the two cuts is 2.1 miles west of the town. Bennett is 2.5 miles south of the junction for the Bennett road (no highway number) and Farm Road 3028 and 8.8 miles southeast of Mineral Wells. Access to the railroad cuts is obtained by a lengthy walk along the tracks. No prior permission is necessary to study the rocks in the railroad right-of-way, but individuals who visit this locality should be on constant lookout for trains. The fences between the tracks and the cliffs are devices for detecting rubble that has rolled onto the tracks from above and are linked to an electric relay system. You are urged not to climb on these fences, inasmuch as this would trigger a false danger signal at the railroad dispatcher's office in Fort Worth.

The Bennett locality is particularly significant because it is the only exposure where all the major facies of the prodelta and delta front are present in a single vertical section. Also, the relationship between faulting and direction of progradation for the deltaic lobe are clearly shown.

Local and regional stratigraphic setting.—The Dobbs Valley Sandstone Member of the Mingus Formation crops out in a more or less continuous belt (figs. 24, 62) from western Parker County to west-central Erath County. At its northeastern extremity, the outcrop belt comprises prodelta, delta-front, and distributary-channel sandstones. In the shallow subsurface downdip from the locality (to the southwest), it can be seen that the deltaic unit exposed at Bennett has very little subsurface expression and rapidly gives way to shallow marine, shelf shales (fig. 27). The main axis of deltaic progradation extends westward from southern Jack County to east-central Throckmorton County; the deltaic complex is extensive and the net-sandstone thickness exceeds 160 feet in several wells. This contrasts with the approximately 70 feet of sandstone present in the Dobbs Valley Sandstone of the Bennett area.

The Dobbs Valley deltaic sequence exposed in the railroad cuts (fig. 63) is part of a small lobate, high-constructive delta system. In the eastern cut (Locality 5A), the delta front is marginal to the main axis of progradation and is composed largely of muddy, coarse siltstone and very fine sandstone. The entire delta front has been intensively burrowed and has a blocky, massive appearance. Also, there is a complete absence of faults in this cliff. By contrast, the western railroad cut (Locality 5B) exposes an unburrowed delta front with easily differentiated delta-front and channel-mouth-bar facies. It is close to the main axis (trending roughly north-south) of progradation. Another lobe of the delta system is exposed on the sandstone-capped hills to the southeast of Bennett.

Overlying the delta-front sandstones (exposed at the top of cut 5A) are fossiliferous, interdeltaic mudstones and the large-scale trough-cross-bedded basal sandstone unit of a distributary channel. The distributary also crops out on U. S. Highway 281, three miles to the west at Locality 6.

Facies composition and inferred depositional processes.—Locality 5B (fig. 63) provides an almost ideal example of the complete vertical sequence for the progradation of a small lobe of a lobate delta complex (fig. 20B). The basal 30 feet of the cliff face comprises the proximal prodelta facies of the Dobbs Valley Sandstone. This facies contains

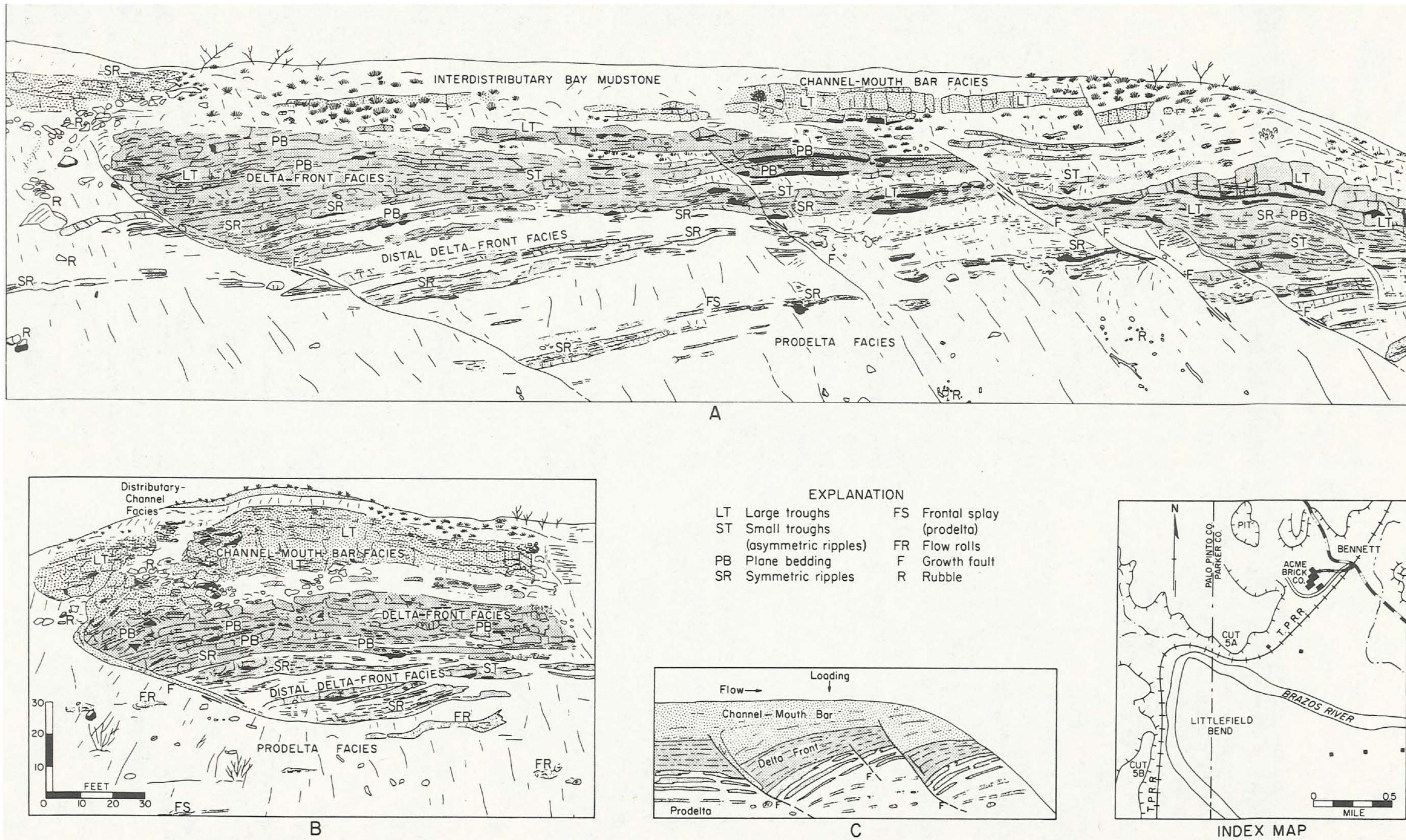

Figure 63. Field locality 5: Delta-front facies, Dobbs Valley Sandstone, along Texas Pacific Railroad, 2 miles southwest of Bennett, Texas. See figs. 55, 62 and index map for location. A. Highly slumped delta-front/channel-mouth bars displaying growth faults. B. Detailed view of contorted growth-fault block. C. Sketch of inferred conditions during growth faulting.

abundant flow rolls, rotated but relatively undeformed blocks that have slid down from the overlying delta-front sandstone facies, as well as thin, more or less continuous flags of silt or very fine sandstone (figs. 63A, 63B). These sandstone bodies are formed from sediment scoured off the channel-mouth bar during periods of flooding. Macerated plant material is exceedingly abundant in both the shales and sandstone flags of the prodelta. Some of the shale is lignitic. Close examination of the more continuous sandstone flags shows that some of these are graded.

There is a gradual increase in total sand upward through the section. Sandstone flags become more numerous and closer together, whereas the shale units first thin and then become thin partings between thick sandstone bodies. The lower part of the delta front at Locality 5B is made up almost wholly of thin flags (0.25 to 2 inches thick) of unburrowed, wave-rippled, well-sorted, very fine sandstone. The symmetrical ripple bedforms and the relative absence of trough cross-beds suggest that marine wave attack reworked a considerable portion of the delta front. Fully half the vertical thickness of the combined delta-front/channel-mouth-bar sandstones is composed principally of silty shale and wave-rippled sandstone flags previously described.

Higher in the delta-front sequence, individual sandstone units become thicker, with horizontal laminations being the most prominent internal sedimentary structure. Small- and medium-scale trough cross-beds are also present and oscillation ripples occur on the surfaces of some of the laminated and cross-bedded units. Deposition of the horizontally laminated units took place in shallow water adjacent to the channel-mouth bar during periods of high discharge. This rapid, though infrequent, reworking of delta-front sands obliterated most of the ripple-cross-laminated bedforms and small-scale trough cross-beds.

The channel-mouth bar at Locality 5B comprises massive (greater than two feet thick), very well sorted, blocky sandstone units that lack significant shale partings. Again, horizontal lamination is the dominant internal sedimentary structure, but large-scale troughs slice into the channel-mouth bar at many points along the outcrop. These troughs represent unobliterated scours gouged through the shallow crest of the bar during floods.

The vertical changes in sediment texture and sedimentary structures thus far described can be termed a progradational sequence. This is also a coarsening-upward sequence to the extent that the total percentage of sand-sized particles progressively increases upward. It is the loss of shale intervals and partings and not the coarsening of the sand fraction itself that brings about the overall net coarsening of the texture. A progradational sequence as it appears on electric logs in the subsurface is illustrated in figure 36.

Significant aspects of Locality 5B are the growth faults in the delta-front and channel-mouth-bar facies (figs. 63A, B). The faults developed in direct response to sediment loading on the crest of the bar, with fault movement probably taking place during the entire period of bar deposition. The fault plane is concave toward the direction of progradation, and individual facies involved in the rotational slumping are thicker on the northern (downstream) side (fig. 63C) of the fault. Within any single growth-fault block, beds are thickest and the massive channel-mouth bar is best developed proximal to the distributary channel. The maximum dip of the sandstone flags in the fault blocks is roughly 10° at Bennett, but exceeds 70° at Locality 9 in the Avis Sandstone (Cisco Group). Beds adjacent to the fault can be highly deformed where individual beds have been dragged downward parallel to the plane of slumping. A particularly good example of this drag phenomenon occurs at the south end of the railroad cut (fig. 63B) where sand from the basal part of the channel-mouth bar was sucked downward as slumping began and spread out along the entire trace of the fault plane.

The south-facing railroad cut, Locality 5A, has markedly different delta-front facies characteristics from those described for Locality 5B (fig. 63). The only similarity is in the prodelta facies composed of siltstone and very fine sandstone flags of the progradational sequence. Also, the best-developed flow rolls in the Bennett area occur at the east end of the 5A road cut. The delta-front facies is finer grained at 5A, with coarse silt being the median grain size. No distinct channel-mouth bar is present and the delta front lacks the abundant wave-rippled flags so prominent at 5B.

The blocky, massive appearance of the delta front at Locality 5A results in large part from intensive burrowing by the infaunal benthos (bivalves, crustaceans, and polychaete worms). These burrows include both tubular networks (individual tubes commonly have diameter of a pencil) utilized for dwelling purposes and fanlike burrows oriented parallel to bedding planes. These arborescent burrows constructed along bedding planes are the feeding marks of infaunal nonselective deposit feeders. Their abundance is the result of a moderately slow sedimentation rate and the relative absence of direct fluvial influence or marine reworking. In addition to the burrows, other evidence of organisms include comminuted fragments of spiriferid valves, crinoid ossicles, and rarely a whole astartid or nuculid bivalve.

The delta front of Locality 5A was laid down lateral to the main axis of delta-lobe progradation (as exposed at Locality 5B). The finer sediment size, calcite cement, heavy bioturbation, and presence of indigenous fossils all support deposition in an embayment protected from direct marine reworking. Also, the absence of a channel-mouth bar indicates a lack of direct feeding from a distributary channel.

Overlying the delta-front facies are a slightly fossiliferous, interdistributary-bay mudstone and distributary-channel fill. The channel is filled with large-scale troughs at the base; at the west end of the cut, the distributary deposit is somewhat thicker. Sedimentary structures in the basal several feet of the distributary have been partially effaced by soft-sediment deformation. Several large blocks of the distributary deposits have detached from the main body and now rest halfway down the slope.

Depositional summary.—Lobes of small, high-constructive lobate deltas prograded westward and southwestward across eastern Palo Pinto County during deposition of the Dobbs Valley Shale. Discharge in this area was into the shallow water of a marine embayment well to the south of the main Dobbs Valley delta system. Locality 5B affords an excellent example of a deltaic, progradational, coarsening-upward sequence where the lignitic silty shale of the prodelta gives way upward to the wave-rippled flaggy sandstone of the delta front and the scoured, clean, horizontally laminated sandstone of the channel-mouth bar. Excessive loading of sediment on the channel-mouth bar caused the development of curved growth faults along which progressive slumping took place as additional sediment was transported to the delta front. A fossiliferous interdistributary mudstone and the base of a distributary channel make up the topmost facies of the deltaic cycle in the Bennett area.

Locality 6: Delta-Plain Distributary-Channel Fill, Dobbs Valley Sandstone

Significance and location.—A thin distributary-channel-fill sandstone has cut into interdistributary-bay mudstones near the top of the Dobbs Valley Sandstone Member of the Mingus Formation (figs. 55, 62). Locality 6 is a road cut on the east side of U. S. Highway 281, approximately 8.8 miles south of Mineral Wells. This stop illustrates in detail the internal sedimentary structures and geometry characteristic of channel fill in a small distributary (fig. 64). It is part of the same distributary complex that is present at the top of Localities 5A and 5B. The locality is of particular interest in that the base of the channel fill is undeformed and that the vertical sequence of sedimentary structures throughout the channel is well preserved.

Local and regional stratigraphic setting.—The regional stratigraphic setting of the Dobbs Valley Sandstone has been described for Locality 5 and will not be restated in detail here. This unit crops out as a continuous belt having a strike of N 41° E through Palo Pinto County and a dip of about 1° NW. Overlying the distributary sandstone is a thin veneer of fossiliferous, marine-reworked, calcite-cemented sandstone and sandy limestone termed the Goen Limestone. The exposure of marine shale interbedded with and above the Goen Limestone at Goen Cemetery (fig. 63, index map) is one of the most prolific fossil-collecting localities in the Strawn. A coal unit, the Thurber Coal, occurs within this interval both to the north in Central Parker County and to the southwest near Gordon and Strawn, but is absent in the Bennett area. Both the surface lithology and the subsurface map for the upper part of the Mingus Formation (fig. 28) indicate that the shale unit is part of an extensive marine embayment positioned southwest of the main locus of deltaic progradation.

Facies composition and inferred depositional processes.—The facies present at Locality 6 (fig. 64) include: 1) a thin, unfossiliferous interdistributary-bay mudstone at the base of the cut; 2) the distributary-channel-fill sandstone; and 3) delta-plain mudstones. The interdistributary mudstone contains rare macerated plant fragments, but lacks the brachiopod and crinoid fauna noted in the same facies at Locality 5A.

The base of the distributary has a sharp, scoured contact with the underlying mudstone. In contrast to the basal zone of larger distributary channels (figs. 13B, 15B), the lower portion of the distributary channel at Locality 6 displays only minor distortion. This results from the fact that the entire thickness of the sandstone fill is less than 20 feet and that the underlying mudstone facies is probably only half that thick. Hence, there was neither sufficient sand to induce load deformation nor

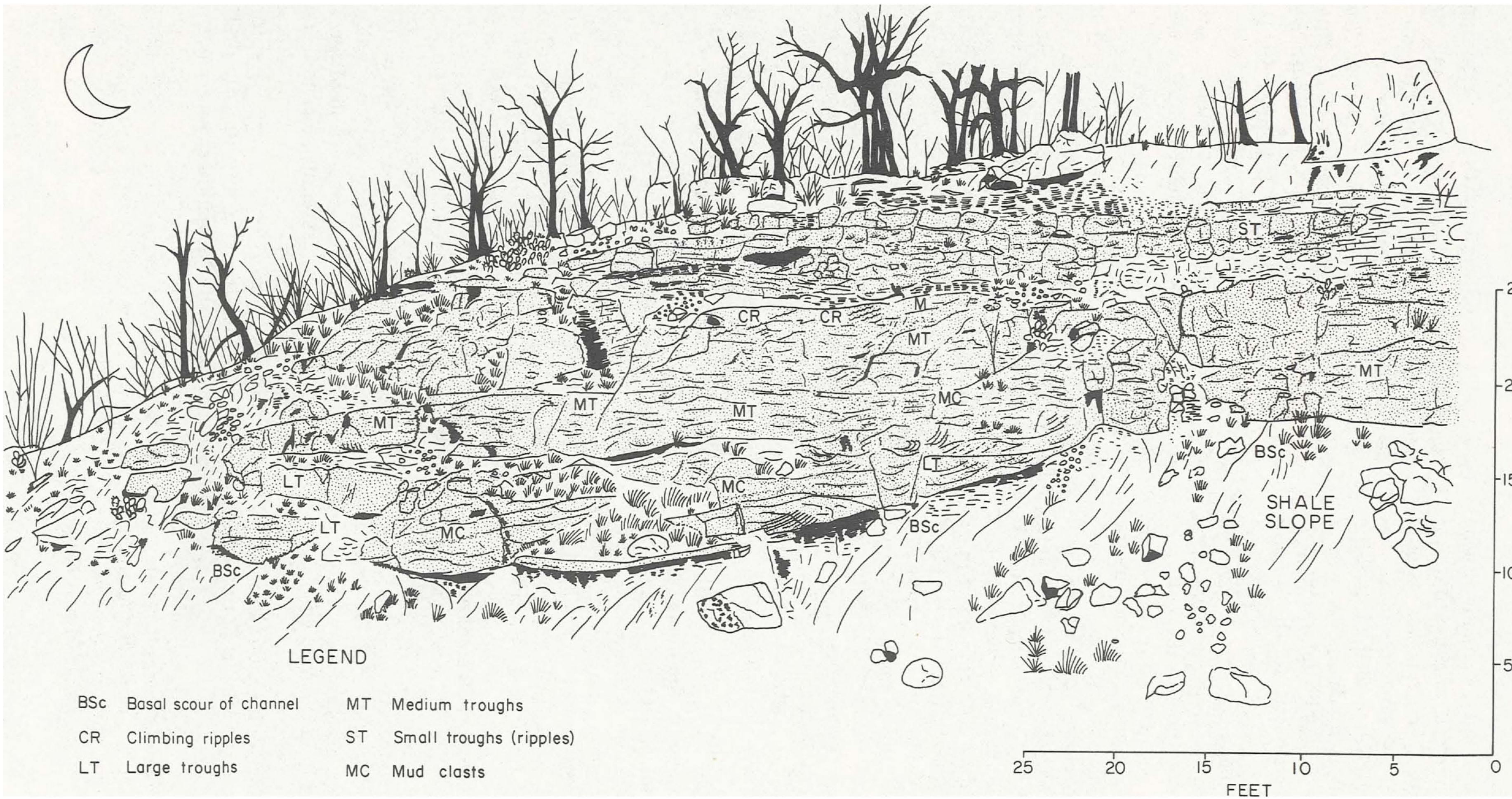

Figure 64. Field locality 6: Distributary-channel-fill facies, Dobbs Valley Sandstone, along U. S. Highway 281, Palo Pinto County, Texas, See figs. 55, 62 for location. Stratigraphically overlies delta-front facies at Locality 5.

sufficient mud to initiate failure. It might also be anticipated that such a small channel did not deposit a channel-mouth bar and was rapidly abandoned in favor of a second, unexposed channel. The distributary channel at the top of the Locality 5A railroad cut is much thicker with a basal massive zone that is highly deformed; it is most likely the master distributary for the Bennett deltaic lobe.

Large-scale troughs, many of which contain abundant pebble-sized clay chips, are the predominant sedimentary structures in the bottom 5 feet of the channel fill. These clay chips were eroded from the underlying mudstone and line the basal scours of individual troughs. The chips are also abundant in the overlying zone of medium-scale cross-beds. Higher in the section, the fine-grained sandstone lacks any coarse clasts and is composed of small-scale trough cross-beds and ripple-drift cross-laminations. The climbing ripples are particularly numerous away from the center of the channel (southeast side of outcrop). The abrupt change from sandstone to mudstone at the top of the section indicates that the distributary was rapidly and permanently abandoned, for the superjacent fines represent sediment settling out from suspension. Contrast this situation with that described for the top of the distributary-channel-fill facies at Locality 7.

Vertical aggradation of the channel fill was clearly the dominant process in the deposition of the sandstone unit. Although there is an apparent fining upward from the scour at the base of the channel, there is a complete absence of lateral accretion (fig. 12B; discussion of Locality 15). Also, comparison of the vertical sequence of sedimentary structures at Locality 6 with the ideal vertical sequence for a point bar (fig. 15D) indicates that two of the most prominent elements of the point-bar sequence, parallel lamination and tabular cross-bedding, are virtually absent in the road cut. Neither the braided stream nor coarse-grained meanderbelt models (fig. 15A, C) provide for vertical sequences even remotely resembling the succession of structures seen in the road cut.

Locality 7: Reworked Delta-Front and Delta-Plain Facies, Uppermost Mingus Formation

Significance and location.—A rippled, intensively burrowed, marginal delta-front facies is overlain by the thin, slightly fossiliferous, coal-bearing shales of an interdistributary bay and the massive, deformed fine sandstone of a small distributary channel (fig. 65). All of the rock cropping out below the cliffs rimming the lake and valley at Locality 7 are part of the Mingus Formation. The sandstone and conglomerate forming the cliffs are of the Brazos River Formation. Locality 7 is at the spillway at the east end of Lake Palo Pinto (figs. 55, 62). It is one mile west of Farm Road 4 on an unnumbered road and is 5.4 miles north of the town of Santo. The spillway is the property of Brazos Power and Light Company and prior permission should be sought before entering the property.

The locality is particularly significant because it demonstrates a variety of different delta-plain environments. The two fluvial sandstone bodies exposed in the spillway area can be studied not only from the standpoint of vertical changes in sedimentary structures but also from that of lateral changes in facies. Detrital coals occur both in the interdistributary-bay mudstone and in the mud plug overlying the distributary channel. The distributary channel exposed in the spillway is a trunk stream for a minor deltaic lobe and was reoccupied from time to time long after avulsion shifted the main site of deposition. Discussion of the vertical sequence and depositional environments represented by the sandstone units in the cliffs rimming the lake (Brazos River Formation) will be provided in the description of optional localities C, D, and E.

Local and regional stratigraphic setting.—The upper part of the Mingus Formation forms a continuous belt of outcrop through Palo Pinto County that trends N 41° E, as does the underlying Dobbs Valley Sandstone (fig. 62). Subsurface mapping of the upper Mingus (fig. 28) indicates that deltaic distributaries shown in outcrop prograded only a short distance to the west. The major delta system within this stratigraphic interval occurs in the shallow subsurface of Jack and Young Counties; the interval in western and northern Palo Pinto County was principally a large interdeltaic embayment. Deposition of the Thurber Coal took place in the swamps, marshes, and in the shallow marine bay just west of Locality 7. Distribution of the Dobbs Valley Sandstone (fig. 27) shows that the coal unit directly overlies the distal ends of thin distributary sands and may, in part, represent the marine-destructional phase for the local deltaic cycle. The base of the section exposed in the Lake Palo Pinto spillway area is roughly 60 feet above the Goen Limestone (figs. 24, 62).

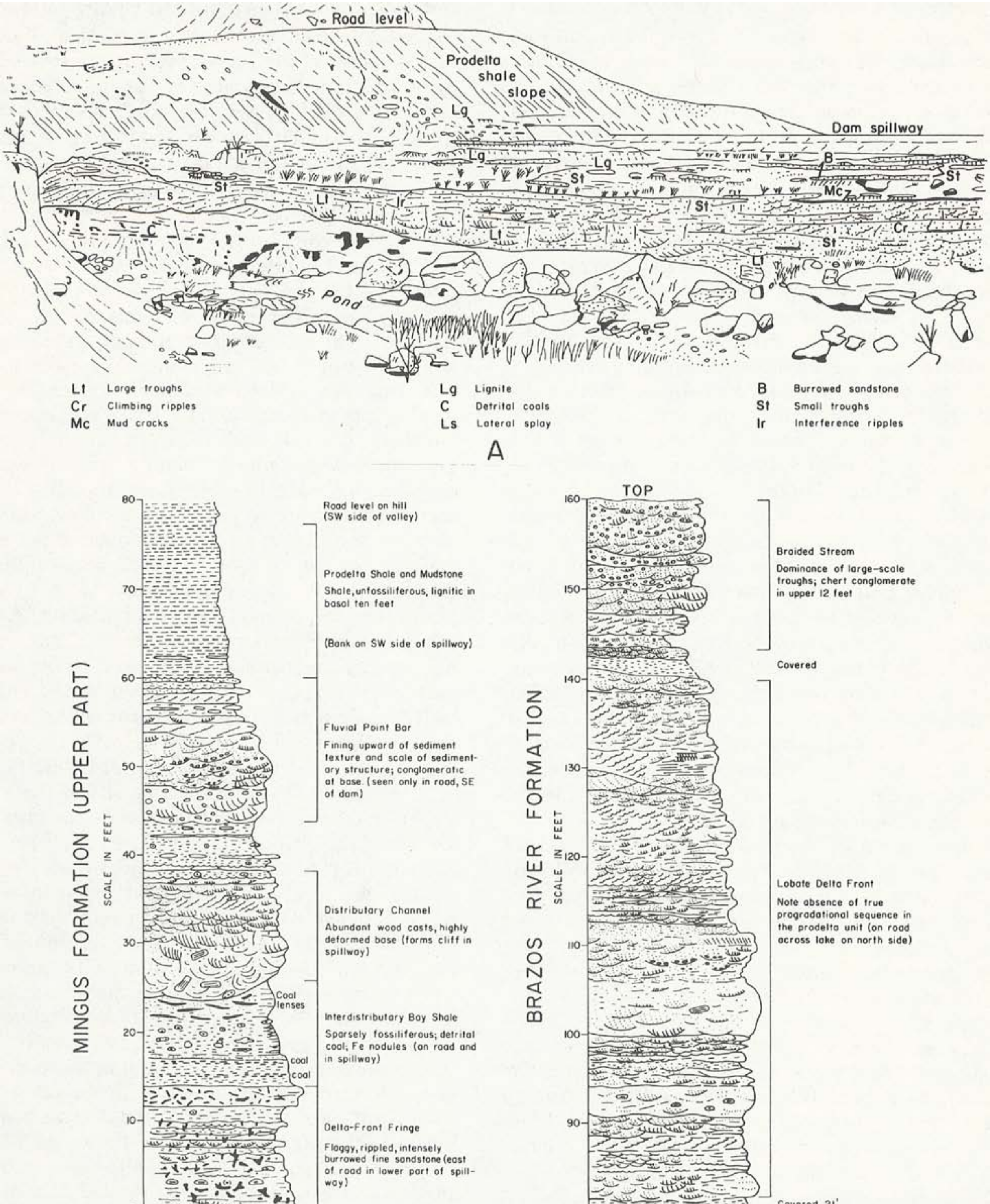

Figure 65. Field locality 7: Small distributary-channel-fill deposit, upper part of Mingus Formation, at spillway, Lake Palo Pinto, Palo Pinto County, Texas. See figs. 55, 62 for location. A. View of distributary-channel facies in spillway cut. B. Measured section of facies, upper part of Mingus and Brazos River Formations.

Facies composition and inferred depositional processes.—At the base of the spillway on the south bank, the upper part of a reworked delta-front facies is exposed. The flaggy, oscillation-rippled, very fine sandstone is calcite cemented and completely riddled with burrows (fig. 65B). Some burrows are in thin tubular networks oblique to bedding, while others form complex arborescent patterns parallel to the bedding planes. The lebenspuren parallel to bedding are the foraging marks of nonselective deposit-feeding organisms. Deposition and marine reworking were not rapid enough to efface the evidence of organic activity. The unit is marginal delta front, similar to the delta-front sequence exposed at Locality 5A.

A thin interdistributary-bay shale separates the delta-front facies from superjacent distributary-channel sandstone. Bay shale is more than 9 feet thick along the road, but has been completely cut out by the distributary in the center of the spillway. Two thin coal zones crop out within the bottom 4 feet of the shale. Both coals have a detrital origin, for the organic material is composed of finely macerated, herbaceous plant debris oriented parallel to bedding. There is no woody debris in the coal or evidence of root casts in the shale beneath the deposits. Apparently, the bay contained at least brackish water, for it supported a sparse fauna of gastropods, pectinids, and astartid bivalves. In the topmost two feet of the bay facies, the shale gradually becomes more silty. There also are thin seams of charcoal, indicating the former presence of woody material.

The distributary-channel-fill deposit is a spectacular sandstone body to study either in the spillway or in the road cut on the southeast side of the valley. Along the road, the base of the channel has been severely deformed from loading and few sedimentary structures of any kind remain. Most significantly, however, the lowest three feet of the channel are completely choked with logs. Pith casts of *Calamites*, impressions of bark from other tree ferns, and fragments of charcoal are randomly spread throughout the jumbled sandstone. Apparently, when the distributary formed by avulsion from an adjacent channel, it carried along a large amount of coarse plant debris swept up from the delta plain.

Near the center of the spillway the logs are less abundant, but the basal part of the channel fill is far less deformed (fig. 65A). Large-scale troughs make up the lowest 3 to 5 feet on the cliff wall of the distributary. Above the large-scale sedimentary structures are medium- to small-scale trough cross-beds and thick beds comprised wholly of climbing ripple cross-laminations. At the southwest corner of the spillway, the large-scale troughs are replaced by a zone of large-scale tabular avalanche cross-beds; this may represent a small splay that cut through the underlying bay muds roughly perpendicular to the axis of the main distributary.

Higher in the channel deposit, individual sandstone beds become thinner and more flaggy and the muddy partings become more abundant and thicker until the channel fill is almost wholly mudstone on the flats between the spillway cliff and the concrete barrier forming the top of the spillway. The numerous thin flags are composed largely of ripple-drift cross-laminations, but oscillation ripples and even mudcracks occur on some bedding-plane surfaces. The shale and mudstone interbedded with and adjacent to the rippled sandstone flags contain several zones of bedded, detrital coal. Apparently, when the distributary segment was abandoned for a more efficient channel, the coal and shale accumulated when fine material could slowly settle from suspension through the ponded water. From time to time, during periods of high flow over the entire delta lobe, however, the abandoned distributary was temporarily reoccupied and thin ripple-bedded sand or silt flags were laid down in the channel bed. Many of these flags are burrowed, attesting to the fact that marine waters repeatedly invaded the lower reaches of the abandoned distributary. The lignitic shale in the lowest part of the shale cliff (fig. 65A) formed the remainder of the clay plug that filled the channel.

At the top of the road cut, just before the road reaches the level of the spillway flats, there is a second fluvial sandstone body completely unlike the distributary unit (fig. 65B). Although this channel fill also contains numerous large-scale troughs in the lower part of the channel, the sediment fill is chert-arenite pebble conglomerate rather than fine sandstone quartzarenite. The coarse channel fill fines rapidly upward and the large-scale troughs give way to small-scale trough, ripple-drift, and rare small tabular cross-beds. In the highest recognizable part of the upward-fining fluvial unit, parallel-bedded silty clay partings alternate with thin, oscillation-rippled flags of very fine sandstone. On Farm Road 4, 0.2 of a mile north of the junction with the Lake Palo Pinto road (fig. 62), this same channel unit crops out, minus the conglomeratic base. At the location on Farm Road 4, the sandstone unit displays accretionary topography; the fining upward of sediment texture, upward decrease in scale of sedimentary structures, and the accretionary topography are all evidence for a point-bar deposit (figs. 12, 15D).

The shale in the large northeast-facing cliff adjacent to the spillway at Locality 7 is highly lignitic and contains cross-laminated siltstone lenses low in the section, but it becomes less lignitic higher and loses the lenses of coarser sediment. The lower, siltier, plant-rich shale is the lateral equivalent of the fine-grained meanderbelt channel fill (point bar). Thus, the lower part of the shale is composed of interfluvial delta-plain facies. The higher 70 feet of unfossiliferous mudstone and shale at the exposure are prodelta facies of the superjacent Brazos River system.

Depositional summary.—A thin, heavily burrowed marginal delta-front sandstone is capped by a thin, sparsely fossiliferous interdistributary-bay facies containing several thin seams of detrital coal. A small distributary cut through the bay mudstones, carrying as bed load large logs derived from a nearby delta swamp. Where the distributary sand had at least several feet of mud below it, loading (and the resultant lateral displacement of the water-saturated mud) brought about severe deformation of the sand in the lowest part of the channel fill. Where the distributary cut down to the top of the delta-front sand, there was no deformation and large-scale trough cross-beds are well preserved. Avulsion upstream caused the distributary segment to be abandoned; mud and finely divided plant detritus settled from suspension to form a mud plug. Occasional short-lived reoccupation of the channel during peak discharge led to the deposition of thin sandstone flags in the predominantly mud section. As the delta lobe prograded westward, small meandering streams appeared in upstream (landward) parts of the delta plain. Upon abandonment and foundering of the deltaic lobe, local marine transgression brought to an end the delta cycle in central Palo Pinto County.

Optional Locality F: Tidal-Channel Deposition During Final Delta Destruction, Uppermost Wolf Mountain Shale

Tidal channel-fill deposits in the uppermost Wolf Mountain Formation indicate tidal activity immediately prior to the initial shoaling that resulted in deposition of the thick Winchell carbonate bank (fig. 35). Locality F occurs along U. S. Highway 180 immediately below (and east of) the massive Winchell Limestone, about 0.7-mile east of the intersection of U. S. Highway 180 and Farm Road 16 at Brad, Palo Pinto County, Texas (figs. 55, 67C).

The channel fill is underlain by a sequence of delta-plain facies including upward: 1) thin, highly burrowed lagoon or interdistributary-bay shoreface deposits; 2) splaylike sandstones and siltstones exhibiting a coarsening-upward sequence of siltstones and trough-cross-bedded sandstones containing clay chips, plant debris, climbing ripple cross-laminations, rib-and-furrow ripple cross-laminations, and locally deformed sandstones; and 3) unfossiliferous laminated mudstones and thin sandstones of possible flood-basin origin. This sequence represents final Perrin delta deposition within the uppermost Wolf Mountain Formation (fig. 35).

The superimposed tidal-channel fill is composed of calcite-cemented coarse pebbles and sand and shell debris up to 2 inches in diameter. The deposit is rich in broken *Myalina* shells, crinoids, rock fragments, and ferruginous claystone concretions. Basal tidal-channel-fill deposits are massive; the upper 4 feet is finer, well-sorted, indurated biosparite. Fifteen feet of sandy and silty mudstone above the tidal channel represents reworked relict deltaic facies within the transgressive marine shelf environment that preceded Winchell Limestone deposition. The Winchell rests almost directly upon deltaic facies elsewhere along its outcrop.

Locality 8: Progradational-Aggradational Facies, Small Delta Lobe, Uppermost Wolf Mountain Shale

Significance and location.—A series of small, high-constructive deltas in the Wolf Mountain Shale served as a stable platform on which an extensive carbonate bank developed (fig. 67). The deltas, which prograded across southwestern Palo Pinto and southeastern Stephens Counties (figs. 34, 67C), provided shoal-water conditions which allowed initiation of Winchell Limestone deposition. A small deltaic lobe is exposed in a road cut on the north side of Farm Road 207, about 5.5 miles west of its intersection with Texas Highway 16 (at Strawn) at the Palo Pinto-Stephens County line (figs. 55, 66). Proximal prodelta, delta-front/channel-mouth-bar facies are well exposed; superposed channel-fill facies are poorly exposed. This deltaic system (fig. 67C) is not part of the principal Perrin delta system to the north.

Facies composition and inferred depositional processes.—Several feet of proximal prodelta mud-

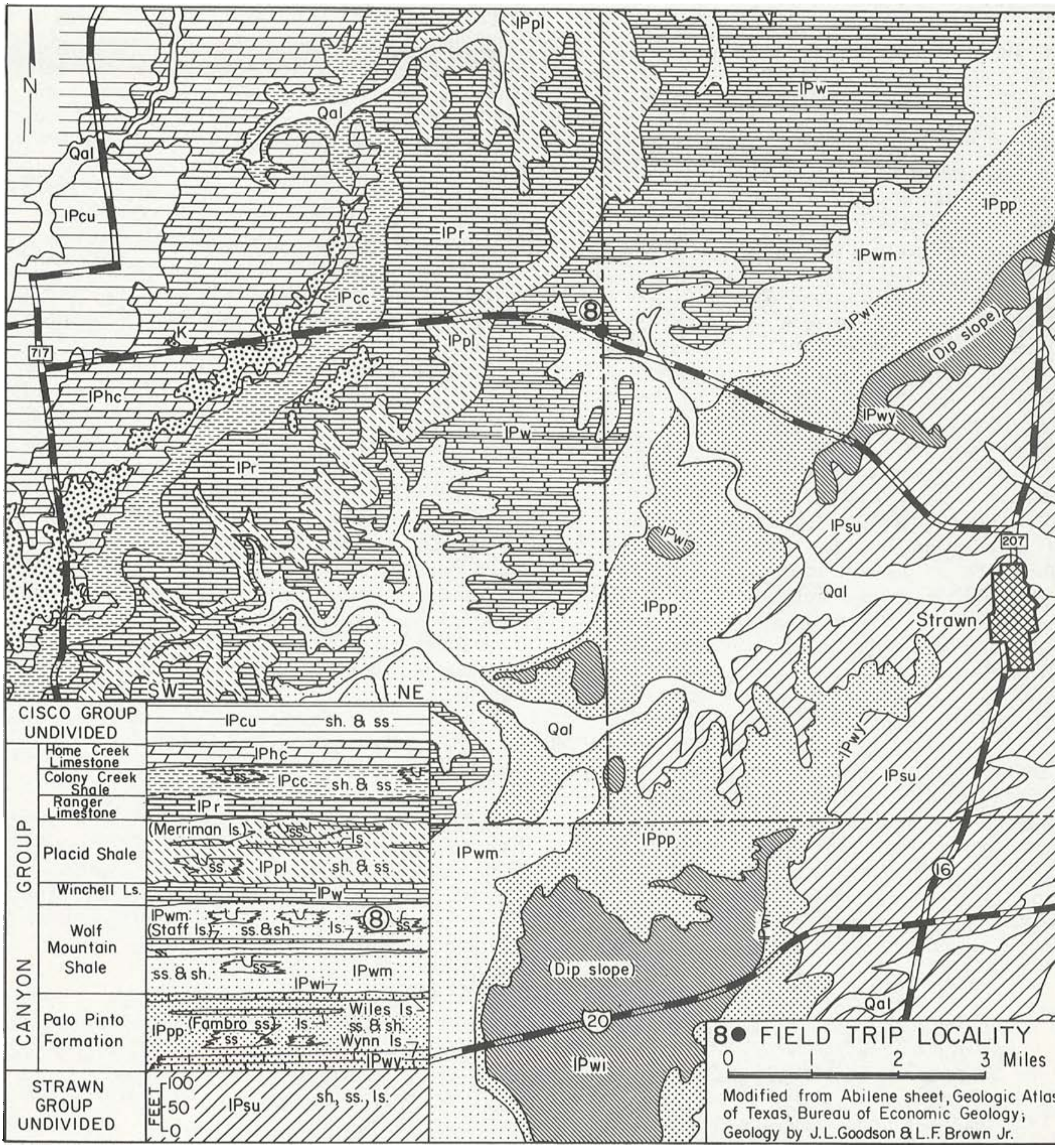

Figure 66. Geologic map, Canyon Group, Strawn area, North-Central Texas. Adapted from Abilene Sheet, Texas Geologic Atlas (1972). Number refers to field locality.

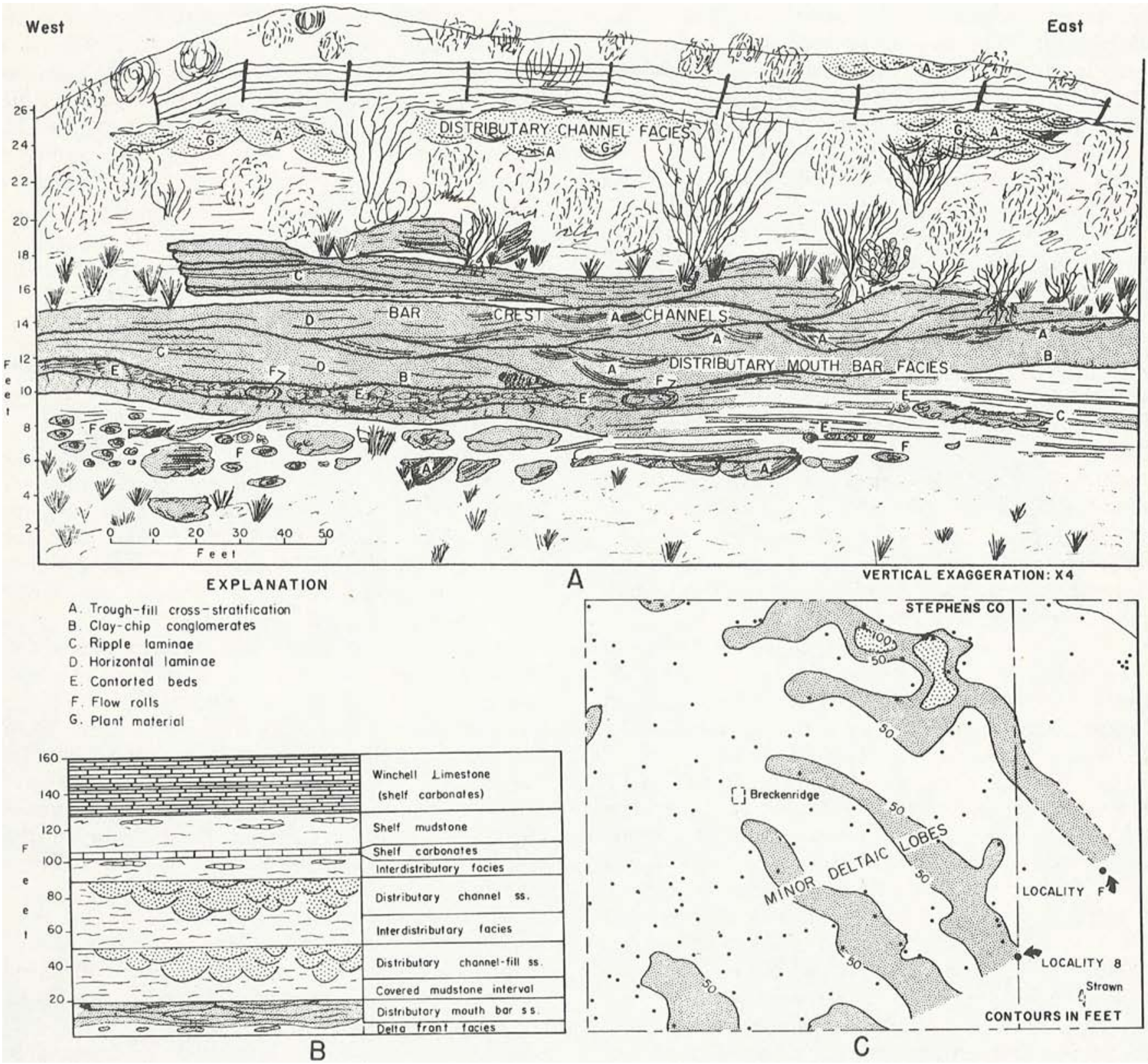

Figure 67. Field locality 8: Deltaic sequence in a small delta lobe, upper part of Wolf Mountain Shale along Farm Road 207 on Palo Pinto-Stephens County line. See figs. 55, 66 for location. A. Channel-mouth-bar facies with superposed distributary-channel-fill deposits. B. Measured section showing facies interpretation. C. Net-sandstone map of Wolf Mountain Shale in this vicinity.

stone containing minor flow rolls and other soft-sediment deformational structures are exposed at the base of the road cut at Locality 8 (fig. 67A).

Channel-mouth-bar facies capped by inferred bar-crest scour channels (fig. 20) are superposed on the prodelta mudstones. Shallow channels in the bar crest probably represent environments transitional between distal distributary channel and channel-mouth bar; the scour channels were cut and filled only during periods of peak discharge. The basal bar facies is fine- to very fine-grained sandstone with abundant plant debris. These lower beds have been deformed by compaction and sediment loading.

The upper (bar-crest) facies are more massive, lens-shaped sandstones which probably represent channel-mouth-bar-crest deposition with aperiodic episodes of scour. Clay-chip lenses are common; uppermost beds also display ripple cross-laminations of possible subaqueous levee origin.

Trough cross-beds occur within the bar-crest facies; much of the bar crest, however, is typified by horizontal laminations representing high flow regime on the shallow bar crest; trough cross-beds occurred either farther down the frontal slope or in scour channels where deeper flow remained in the lower to transitional regimes.

At Locality 8, about 15 feet of partly covered sandy and silty shale overlies the principal sandstone unit; this unit may represent delta-plain or interdistributary-bay facies. Its delta-plain origin is substantiated by the presence of several medium-grained, massive channel-fill sandstones of probable distributary-channel-fill origin (fig. 67A, B). The channel fill is composed of medium- to large-scale trough-cross-bedded sandstones containing abundant wood fragments up to 3 or 4 inches long (fig. 13).

Following delta-plain deposition (mudstones and channel-fill sandstones), the lobe was abandoned, followed by compactional subsidence and marine shoaling conditions. Thin limestone beds were deposited over the abandoned channel-fill sandstones; this, and other similar lobes (fig. 67C), provided numerous stable shoals where centers of Winchell Limestone deposition probably originated. Eventual coalescence of these scattered limestone accumulations led to development of the extensive Winchell bank system (figs. 34, 35).

Depositional summary.—Small Canyon delta lobes that prograded northwestward in the vicinity of Locality 8 later provided stable, submarine shoals on which Winchell carbonate bank facies were deposited. The small lobe exposed at Locality 8 is but one of many composing a sandstone trend (fig. 67C) in the area. Progradation of a thin channel-mouth bar over proximal prodelta deposits points to a constructive elongate system (fig. 39). Scoured bar-crest sediments cap the delta-front facies. Superposed delta-plain mudstones are interlaced with small distributary-channel-fill units. Winchell Limestone shoals developed over the lobe. This deltaic-transgressive cycle (fig. 40) is typical for most cratonic delta systems in North-Central Texas.

Locality 9: Delta-Front and Channel-Mouth-Bar Facies, Avis Sandstone

Significance and location.—Distal prodelta facies of the Wayland Shale is overlain by well-bedded delta-front sandstones and highly deformed channel-mouth-bar facies of the Avis Sandstone (fig. 69). Locality 9 is in an abandoned railroad cut on the William Harrison Ranch (formerly Gordon Woods Ranch), 0.25-mile north of U. S. Highway 183, about 10.5 miles northeast of Cisco, Eastland County, Texas (figs. 55, 68). Access is through the Harrison Ranch headquarters; the property can be entered *only* with prior permission. This locality is unique because of the unusually well exposed stratigraphic and depositional relationship between delta-front sheet sandstones and contemporaneous channel-mouth-bar sandstones, as well as the internal character of each facies. Excessive loading of the bar crest near its distributary mouth resulted in growth faulting and compaction. Channel-mouth-bar sandstones dip up to 75° because of subaqueous slump faulting along a curved fault surface (not well exposed).

Local and regional stratigraphic setting.—The Avis Sandstone crops out in a discontinuous belt (fig. 41, 68) marking the updip trunk of extensive fluvial-deltaic sandstones that extend into the subsurface for tens of miles (figs. 43, 44). Locality 9 is situated along one of the principal sandstone belts that parallel paleoslope (fig. 49). The Avis delta-front/channel-mouth-bar sequence exposed in the abandoned railroad cut is part of a small sandstone belt that has been mapped for about 2.5 miles along a northwest-southeast trend; small distributary channels have been recognized within the unit.

The uppermost part of the prodelta sequence (Wayland Shale) is exposed at the base of the railroad cut and in the nearby hill slopes. These Wayland and Avis deltaic facies crop out for several miles north and south of Locality 9 (fig. 68). Locally, the sequence is cut by later fluvial channels which deeply eroded the underlying delta-front and prodelta facies. One such conglomerate-filled channel about 0.5-mile wide cuts the section about a mile north of Locality 9; the fluvial channel, filled with aggradational, trough-cross-bedded gravels of the valley-fill type, trends east-west and can be traced for two or three miles updip on prominent outliers. The tendency for later incised fluvial channels to cannibalize and erode deltaic facies in each delta cycle makes reconstruction of deltaic facies difficult along the Cisco outcrop. In this area the Wayland-Avis deltaic facies compose a small lobate, high-constructive system consisting of many imbricating and coalescing lobes (fig. 19); as delta-building moved basinward, fluvial channels cut into the underlying deltaic facies. For this reason, fluvial facies may predominate in many areas along

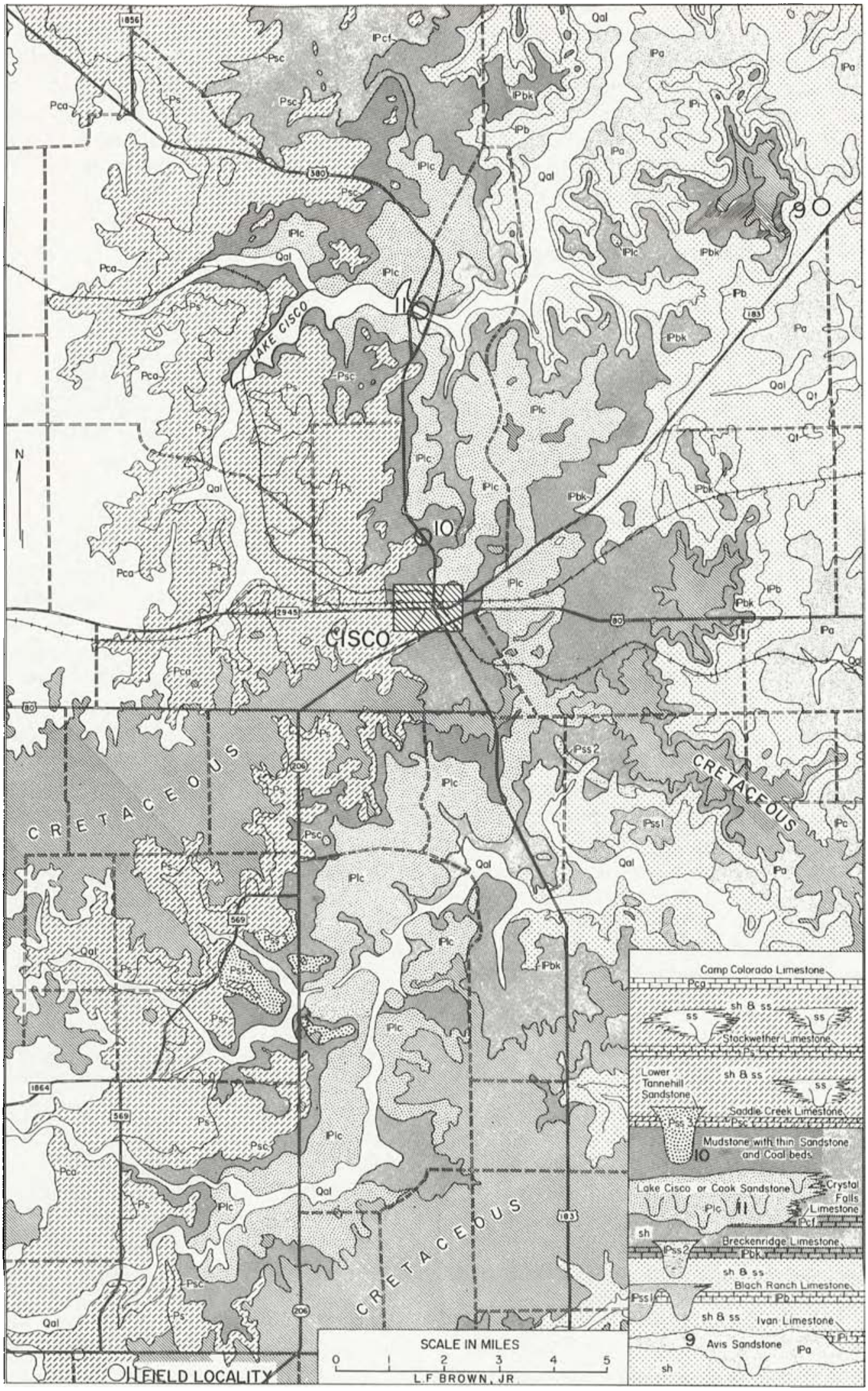

Figure 68. Geologic map, Cisco Group, Cisco area, North-Central Texas. Numbers refer to field localities. Mapping by L. F. Brown, Jr. After Brown, 1969d; reprinted with permission, Dallas Geological Society.

outcrop; preservation of deltaic facies improves progressively westward in the subsurface where less fluvial destruction has occurred.

Overlying the Avis distributary and delta-front sandstones, and exposed in the hill several hundred yards to the west, are delta-plain mudstones, local lenses of calcareous, fossiliferous shale (pinch-out of Ivan Limestone onto delta platform), and sheet- to bar-shaped destructional sandstones. Regressive mudstones, thin coal beds and the transgressive, brackish-water Blach Ranch Limestone complete the destructional-transgressive sequence.

Facies composition and inferred depositional processes.—The internal character of lobate delta-front sandstones and channel-mouth bars is well displayed at Locality 9 (fig. 69). Proximal prodelta shales (Wayland) grade upward into the basal Avis delta-front sandstones. The gradual upward increase in sand content typifies the progradational sequence common in these high-constructive lobate delta sequences (figs. 19, 20B). Although not exposed in the railroad cut (see Locality I, fig. 55), the proximal prodelta normally contains flow rolls and other highly contorted, small sandstone bodies resulting from frontal splaying and slumping during periods of peak discharge. The sheetlike, well-bedded, delta-front sandstones at Locality 9 exhibit some ripple cross-laminations, especially near the base, but these beds are dominantly composed of horizontal laminations; upper surfaces of beds typically display wave or symmetrical ripple bed forms. These shallow-water delta-front sandstones were formed adjacent to and transitional with the channel-mouth bar; high flow within the fresh-water wedge apparently was conducive to deposition of horizontal laminations during brief periods of excessively high discharge. Low-flow-regime ripple cross-laminations are rare and normally confined to basal parts of beds; waning currents probably produced ripple bed forms but long periods of wave oscillation between flood discharge apparently reworked and destroyed these low-flow-regime structures. In a very similar sequence in the Avis (Locality I), flame structures and nearly vertical climbing-ripple-drift structures occur with the dominantly horizontal laminations of the proximal delta-front facies.

The channel-mouth bar at Locality 9 was situated near the point of maximum bar deposition; the bar on the east side of the railroad cut (fig. 69A) is composed of distinctive, very continuous parallel laminations interpreted to have formed at a site that was either at bar crest (high flow regime in very shallow water) or located immediately down the bar slope where periodic high discharge locally and briefly suspended the bedload and redeposited it in parallel laminations. Vertically climbing ripple cross-laminations in this same facies (Locality I) point to exceedingly high discharge, flow regime, and sediment supply. Loading of the channel-mouth bar initiated growth faulting, which progressed throughout bar development; bar deposition was, in part, contemporaneous with deposition of adjacent proximal delta-front sandstones. The parallel laminated sandstone beds dip up to 75 degrees; individual beds display little thickening. The growth-fault block at Locality 9 closely resembles those of the Strawn Dobbs Valley Sandstone (Locality 5). Faulting apparently occurred during excessive loading along a concave-upward fault plane (fig. 63C); motion was rotational with net movement down the bar slope. The curved fault plane apparently originated proximal to the channel mouth; the hinge of the rotating block was distal (fig. 63C). The subaqueous fault resembles rotational slump faults associated with oversteepened and unstable subaerial slopes.

On the west side of the railroad cut at Locality 9 (fig. 69B), the channel-mouth bar is a massive sandstone that displays signs of subsidence, but structures exposed in the west side cannot be directly related to those in the east wall of the cut. The sandstone body on the west wall is shaped like a channel, but a basal erosional contact is very questionable; it appears to represent heavily loaded bar sands that have subsided into underlying delta-front and prodelta facies. The precise geometric relationship between sections of the channel-mouth bar in each wall of the railroad cut (about 25 feet apart) is puzzling. This locality should clearly point out the complex character of facies deposited adjacent to distributary discharge. Other less spectacular examples of these facies occur elsewhere in the railroad cut at Locality 9; each buildup of the bar facies represents a point-source of input from nearby small distributary channels.

Depositional summary.—Small high-constructive lobate delta lobes prograded westward across northern Eastland County on prodelta facies of the upper part of the Wayland Shale. Distributaries were relatively small and discharge was into shallow water. Peak discharge was high but of brief duration. Overloading of channel-mouth bars during high flow regime initiated small growth faults with curved, seaward-dipping fault planes and rotational, downslope motion. Repeated

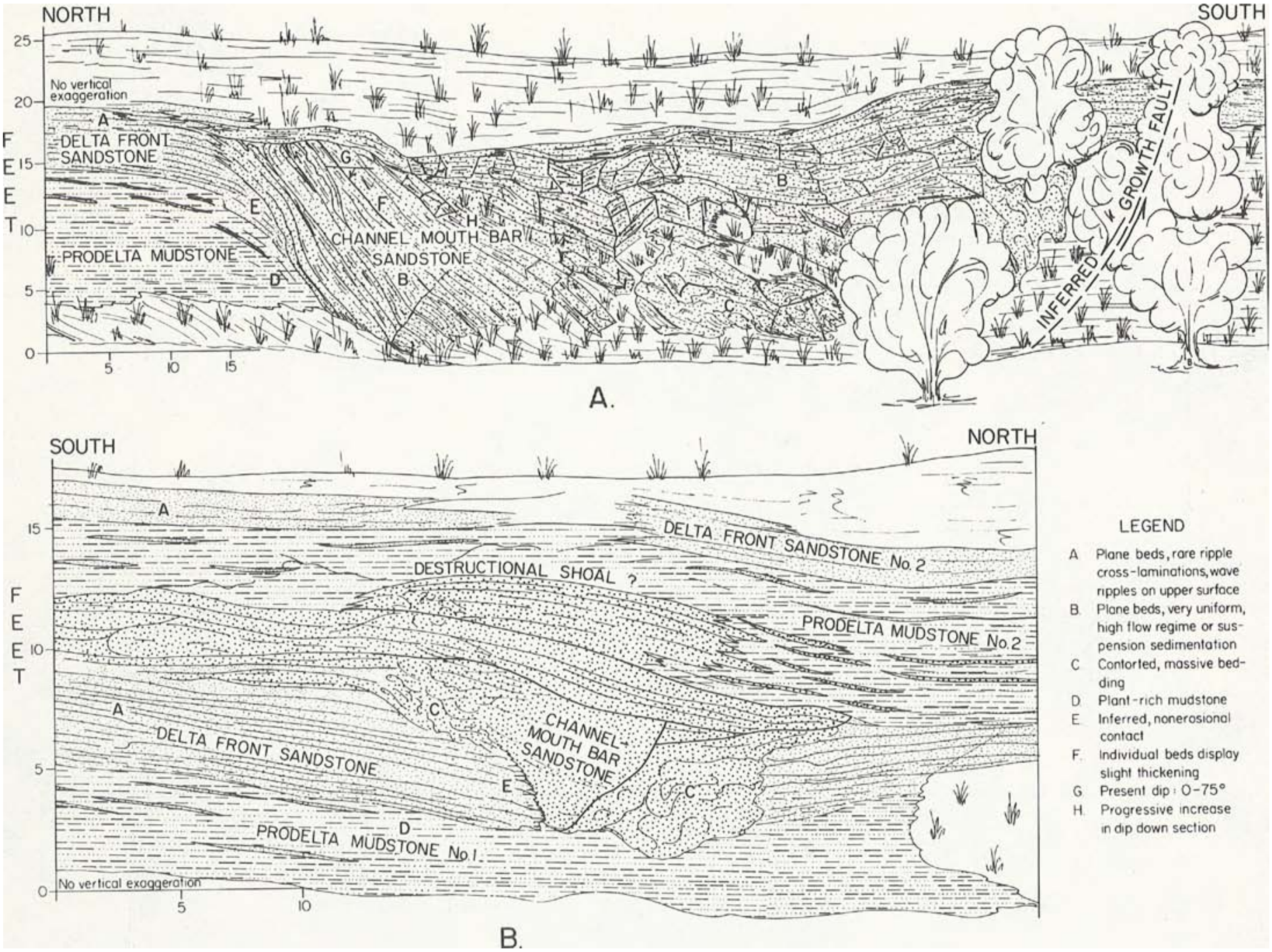

Figure 69. Field locality 9: Delta-front/channel-mouth-bar facies, Avis Sandstone, abandoned railroad cut about 10 miles northeast of Cisco, Texas, 0.25-mile north of U. S. Highway 183. See figs. 55, 68 for location. A. East side of railroad cut showing channel-mouth bar deformed along inferred growth fault. B. West side of railroad cut showing prodelta, delta-front and channel-mouth-bar facies.

deposition reactivated motion until, at present, beds display up to 75 degrees of dip. High flow regime dominated channel-mouth bars and proximal delta-front environments during peak, but short-lived discharge; marine waves modified upper surfaces. Delta-plain mudstones, coal, and marine-transgressive facies complete the delta cycle in the area.

Locality 10: Interdeltaic-Embayment Facies, Harpersville Formation

Significance and location.—Mudstones, sandstones, impure coals, and limestone (fig. 70) were deposited within an interdeltaic embayment located between Flippen and Bluff Creek delta lobes within the upper part of Harpersville Formation, Cisco Group. Locality 10 is located in a road cut along Texas Highway 6 at Cisco Junior College, one mile north of Cisco, Eastland County, Texas (figs. 55, 68).

Interdeltaic-embayment facies, which will be observed again at Locality 14, are principally alternating mudstones, coals, thin, strike-fed sheet sandstones, and thin, impure, brackish-water limestones. Exposures are few and poorly accessible; Locality 10 displays several of the facies that were deposited within these extensive interdeltaic coastal embayments. A proper appreciation of deltaic deposition must include consideration of the variety of interdeltaic facies that were genetically tied to sediment supplied by delta systems

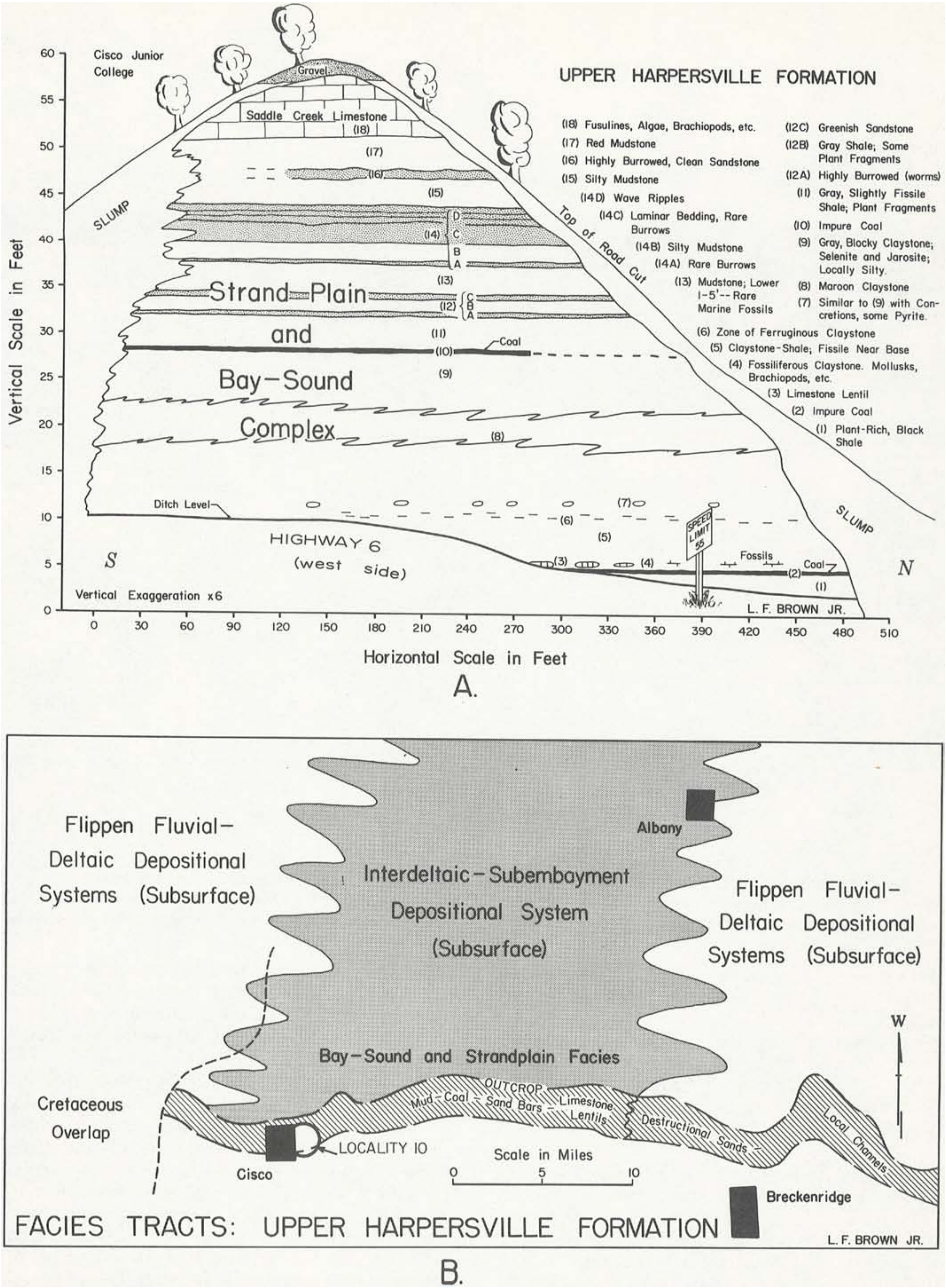

Figure 70. Field locality 10: Interdeltaic-embayment facies, upper part of Harpersville Formation, along Texas Highway 6, one mile north of Cisco, Eastland County, Texas. A. Delta-flank-embayment mudstones, regressive strand-plain facies, and transgressive shelf marine limestone. B. Schematic map of uppermost Harpersville embayment. After Brown, 1969d; reprinted with permission, Dallas Geological Society.

(fig. 22). Interdeltaic facies and inferred environments and processes provide important answers to questions involving sediment dispersal and paleogeographic reconstruction.

Local and regional stratigraphic setting.—Mudstone, coal, and sandstone exposed at Locality 10 (fig. 70) are similar to much of the Harpersville Formation which crops out in southern Stephens and northernmost Eastland Counties (fig. 68). Except for the underlying Lake Cisco (Cook) Sandstone and several minor sandstone units, the Harpersville in the region was principally deposited within a variety of interdeltaic embayment environments (fig. 70B); principal fluvial-deltaic facies occur north and south of the postulated embayment (figs. 41, 51, 70B). These stratigraphic relationships extend westward into the subsurface (fig. 43).

The sequence at Locality 10 directly overlies the Lake Cisco (Cook) Sandstone in the vicinity of Cisco, but the Lake Cisco Sandstone pinches out about 8.5 miles north of Cisco (fig. 41, 68); for many miles north of that point, essentially the entire Harpersville Formation is composed of alternating mudstone, coal, sheet sandstone, and limestones that were fed by Harpersville deltas (fig. 22).

Specific interdeltaic facies in the Cisco Group are difficult to map because they are dominantly mudstone units, lacking the skeletal sandstone facies which aid in differentiating facies. The recurring interdeltaic sequence (or cycle) so well displayed by the Harpersville rocks (Brown, fig. 7, 1960) consists of embayed mudstone facies of sound, bay, lagoon, and/or marsh origin commonly containing thin, impure coals and bituminous shales; this sequence may be locally cut by small tidal and/or distributary channels. Thin, sheet sandstones and local bar-shaped sandstones are normally followed upward by fossiliferous mudstones and limestones.

Facies composition and inferred depositional processes.—The facies at Locality 10 (fig. 70A) rest directly on the top of the Lake Cisco (Cook) fluvial system (Locality 11). It represents embayment deposition shifting from relatively restricted delta-flank bay or sound (mudstones and impure coals) upward to strand-plain deposition (thin burrowed to marine shoal sandstones) and capped by marine-transgressive deposits (fossiliferous shales and limestone). At the base of the sequence are detrital coal and plant-rich fissile shales intercalated with thin lentils containing brackish invertebrates representing brackish bay deposition. These fissile shales grade upward into unfossiliferous, ferruginous claystones with pyrite concretions marking increased restriction; locally oxidized zones indicate possible intertidal or subaerial exposure. These oxidized mudstones are overlain by blocky claystones with jarosite and selenite within the weathering zone; a thin, impure, sub-bituminous coal or lignite bed caps the claystone (see Locality 14, fig. 78).

Following coal deposition, environments became increasingly marine, as evidenced by thin burrowed sandstone and sparsely fossiliferous mudstone. Thin sandstone beds with horizontal laminations and wave-oscillation ripples are followed upward by red, fossiliferous, possibly intertidal mudstones and finally by an open-shelf limestone (Saddle Creek Limestone) containing fusulinids, algae, and brachiopods.

Depositional summary.—Broad embayments between deltaic systems (fig. 21) provided a variety of depositional environments during Cisco deposition. During deposition of the Harpersville Formation, sediment was supplied to the Eastland-Stephens County embayment by strike-fed transport. Uppermost Harpersville facies in the vicinity of Cisco demonstrate progressive filling of brackish bays with subtidal to intertidal muds and detrital plant debris, followed by strand-plain and marine-shelf environments. Strike-feeding of the embayments probably coincided with nearby Flippen delta progradation, followed by strand-plain deposition and marine transgression that correlate with delta destruction and abandonment (fig. 22).

Locality 11: Sequential Development of Complex Fluvial Systems, Lake Cisco (Cook) Sandstone

Significance and location.—The Lake Cisco (Cook) Sandstone in the vicinity of Lake Cisco dam (figs. 71, 72, 73) is a fluvial facies complex composed of meanderbelt point bars, abandoned channel-fill deposits, including splay-fed Gilbert (homopycnal) delta foresets and bottomsets, and superimposed, confined valley-fill conglomerates that grade upward into relatively unconfined braided facies. Recognition of this variety of facies within a mappable sandstone body about 50 feet thick provides insight into the sequential development within Cisco fluvial systems that fed deltas many miles to the west.

The Lake Cisco Sandstone is best exposed in two road cuts along Texas Highway 6 and in two road cuts along a paved road that crosses Lake

Cisco dam (fig. 71B) about 5 miles north of Cisco, Eastland County, Texas (figs. 55, 68). Three localities (11A, B, C; fig. 71B) provide exposures of the variety of fluvial facies within the Lake Cisco Sandstone. Road cuts up to 0.35-mile long are unusual in the Cisco Group, and those at Locality 11 provide a unique opportunity to study the internal character of the system.

Local and regional stratigraphic setting.—The Lake Cisco Sandstone crops out along bluffs in the area (fig. 68), but 5 miles north of Locality 11, the sandstone is replaced abruptly by interdeltaic-embayment facies composed of mudstones, coals, and thin limestones (fig. 41). The system disappears southward along outcrop beneath Cretaceous deposits. Westward, the Lake Cisco Sandstone extends many miles into the subsurface (fig. 50) where the fluvial facies grades down paleoslope into deltaic facies. The fluvial system is erosional at its base and displays internally several erosional unconformities. Regionally, however, the system parallels limestone and coal beds, exhibiting no progressive truncation in subsurface sections.

In the vicinity of Locality 11 (fig. 68), the Lake Cisco Sandstone erosionally overlies 20 to 30 feet of embayment claystones containing the Crystal Falls Limestone; the Breckenridge Limestone crops out in the creek in Lake Cisco Park. The embayment facies exposed at Locality 10 overlie the Lake Cisco Sandstone; Saddle Creek Limestone caps the highest hills in the area.

Facies composition and inferred depositional processes.—Facies within the Lake Cisco Sandstone (fig. 71A) can be divided into three principal groups: 1) point bars related to initial meanderbelt fluvial deposition; 2) complex facies related to post-meanderbelt abandonment and reoccupation of local channels; and 3) deep channel erosion through the meanderbelt system with deposition of aggradational conglomerates within confined channels capped by less confined, possibly braided channel deposits.

Two thin, superposed point-bar sequences are recognized; both are exposed in the south end of the road cut at Locality 11B (fig. 72A, B); the upper point bar is also well exposed at Locality 11A (fig. 73C). These point bars display moderately well developed fining-upward sequences in grain size and in scale of sedimentary structures. Lower point bars are composed of large tabular foreset beds and large-scale trough cross-beds; conglomeratic chert lag is most common at the base. Middle point bars exhibit moderate- to small-scale trough cross-beds and some moderate-

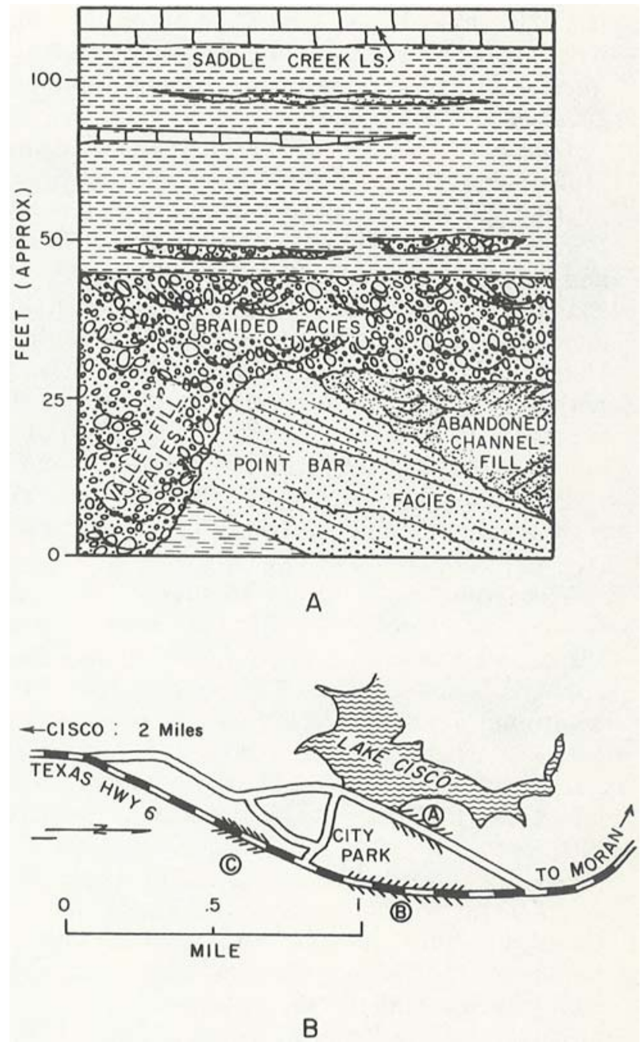

Figure 71. Field locality 11: Lake Cisco (Cook) fluvial system, along Texas Highway 6, about 5 miles north of Cisco, Texas. Refer to figs. 55, 68 for location. A. Composite section of Lake Cisco area. B. Index map to road cuts near Lake Cisco.

scale tabular foresets. Upper point bars are poorly developed but are probably represented by small-scale trough or ripple cross-laminations; ripple-drift cross-laminations may occur locally within the upper bar sandstones. Uppermost silty and sandy mudstones may represent levee deposition; small mud- and silt-filled swale channels cut upper point-bar sandstones.

Point-bar accretion was northward within the road cuts (figs. 72A, B; 73C) as indicated by the inclination of accretionary beds. Sedimentary structures and grain size both diminish upward along each accretional bed from lower point bar to upper point bar (see fig. 12B). Slight shifts in the orientation of accretionary point-bar units indicate

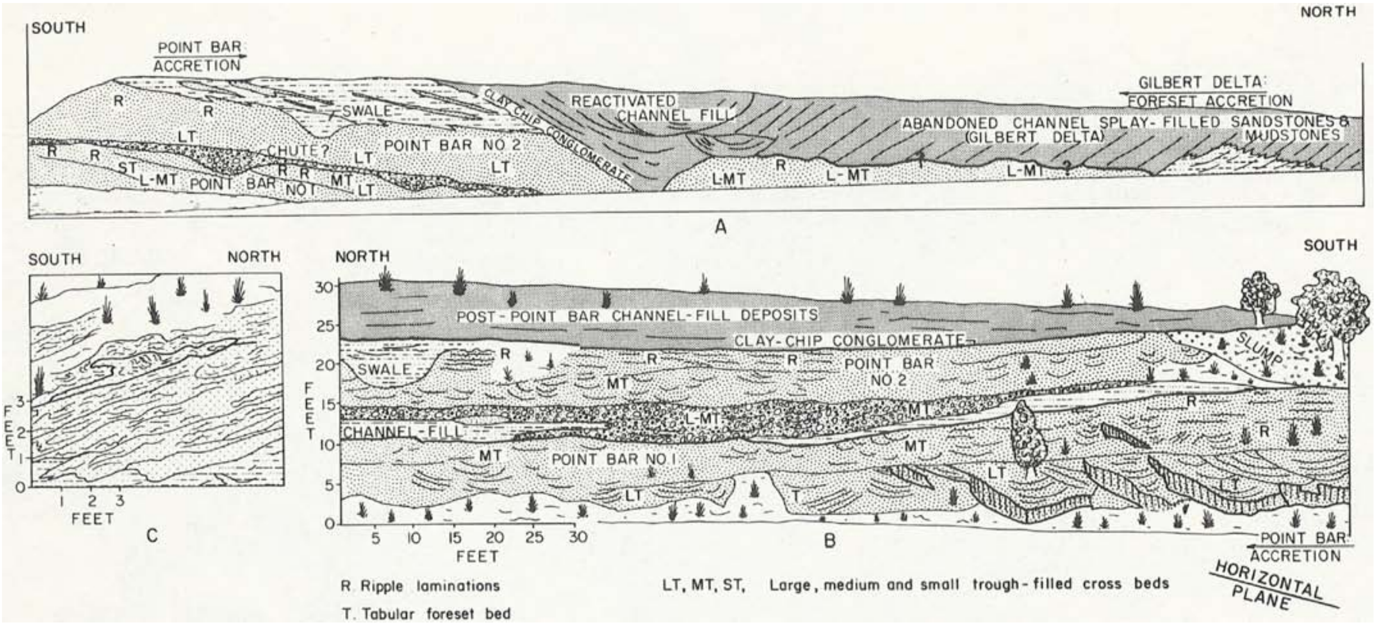

Figure 72. Field locality 11B: Nature and sequential development of Lake Cisco meanderbelt system. See fig. 71 for index map. A. Schematic cross section along west side of road showing point bars and complex abandoned channel-fill deposits. B. Two superposed point bars, east side (south end) of road. C. Steeply dipping, slumped foreset beds, splay-fed Gilbert delta, west side of road (north end).

that the bars were migrating slowly in response to shifts in river course.

Following deposition of the lower point-bar sequence (fig. 72A, B), the channel may have been temporarily abandoned, during which time the point bar was partially eroded and the channel was filled with mudstone. Eventually, the channel was reoccupied, the mudstone fill was scoured, and deposition of the upper point-bar sequence began. A conglomerate-filled channel cut into the lower point bar may represent a chute channel, which suggests low stream sinuosity. The upper point-bar sequence is more completely preserved than the lower, partially eroded bar.

Point-bar deposition within the Cisco meanderbelt at Locality 11 was followed by a complex series of channel abandonment and reoccupation episodes accompanied by many depositional and scour events (Locality 11B). Several clay-chip conglomerates that can be traced through the road cut at Locality 11A, B outline the base of various post-point-bar erosional episodes. The abandoned channel was partially filled from the north by side filling; a splay-fed Gilbert delta prograded southward across the channel (fig. 72A) depositing steeply dipping (30 degrees) foreset and distal bottomset beds. These homopycnal delta foresets built into at least 15 feet of water in the abandoned channel, fed by an active channel to the north. Foreset beds (fig. 72C) are composed of mud-chip conglomerates that display soft-sediment gravity-flow and slump folds; clay chips were probably ripped up by splay channels as they cut into abandoned channel mudstones.

Following foreset deposition, only the central part of the abandoned channel remained unfilled, and it was subjected repeatedly to a complex sequence of reoccupation, abandonment, and some splay-filling before the meanderbelt system was completely abandoned.

At some time following meanderbelt abandonment, the Lake Cisco fluvial system was again reactivated and channels incised deeply into the meanderbelt facies. Erosion was triggered when the profile of equilibrium changed in response to 1) relative differences in subsidence rates between the basin and source area; 2) minor changes in eustatic or relative (subsidence) sea level; and/or 3) the effect of over-extended fluvial systems shifting by avulsion to higher gradient, more efficient routes. In any event, 30 to 40 feet of channel erosion (Locality 11C; fig. 73A) locally cut through the meanderbelt system. Deposition of coarse chert conglomerates occurred within the confined channels; large-scale conglomeratic trough cross-beds indicate the confined nature of the flow within the channels (see fig. 14). As the valleys aggraded and less confined flow was focused in the

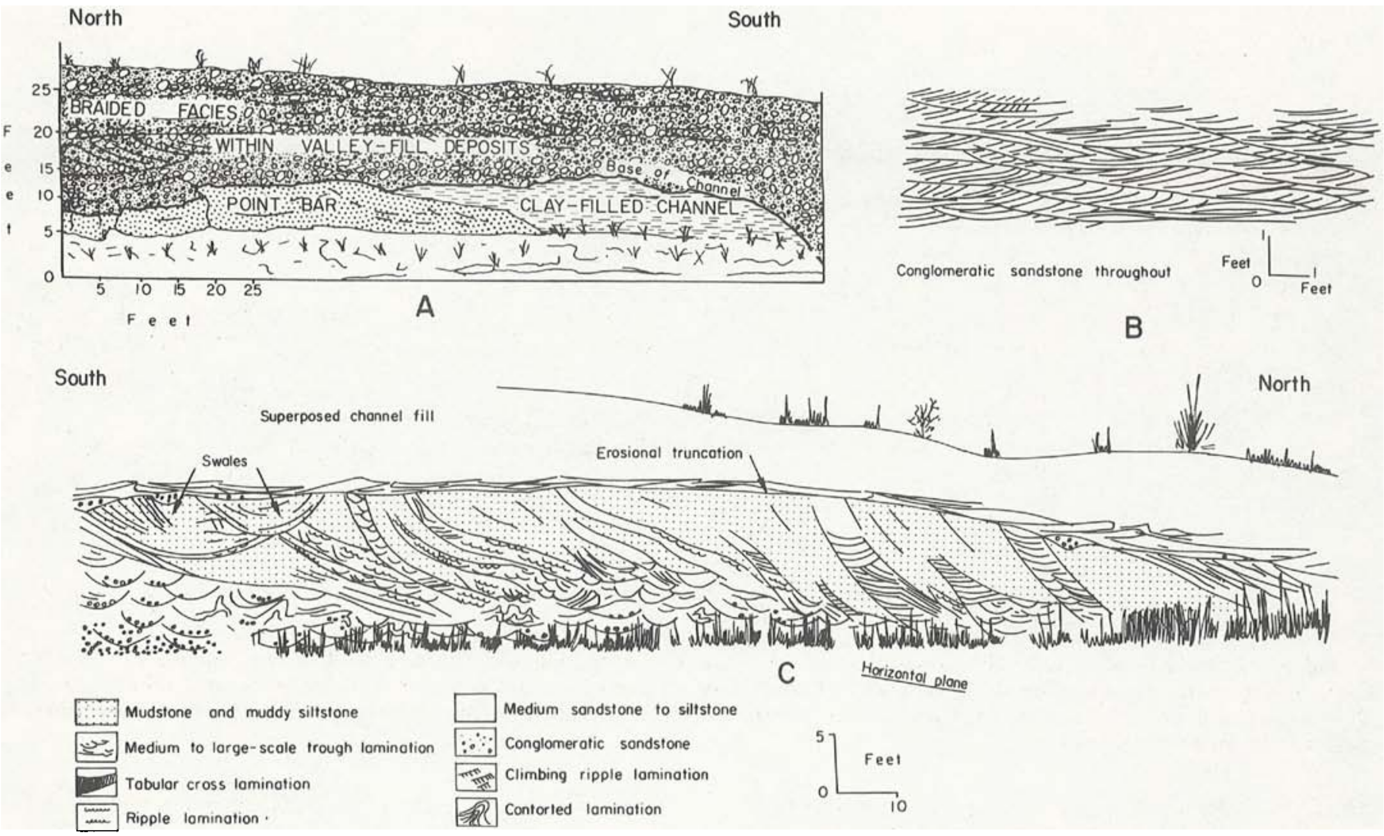

Figure 73. Field locality 11A, C: Variety of fluvial facies, Lake Cisco system. See fig. 71 for index map. A. Meanderbelt sandstones and superimposed valley-fill conglomerate, east side of Texas Highway 6, Locality 11C. B. Trough cross-beds, braided facies, unconfined valley-fill facies, west side of Texas Highway 6, Locality 11C. C. Point-bar facies, west side of road across Lake Cisco dam, Locality 11A.

channels, smaller scale trough cross-beds developed; an upward decrease in gravel content coincided with less confined channel flow. Uppermost valley-fill facies (Locality 11C; fig. 73B) are braided, but they display a predominance of small-scale trough cross-beds resulting from transverse-bar deposition into small wash-out scours (see figs. 10; 15A). The braided facies spread laterally into an extensive, multilateral braided system that marked final deposition of the Lake Cisco (Cook) system. At the time of final fluvial activity, the system was supplying sediment to deltas more than 40 miles to the west (fig. 50).

Depositional summary.—The Lake Cisco fluvial system underwent a sequence of distinctive depositional and erosional events including meanderbelt (point-bar) development, a complex history of abandonment and reoccupation, superposition of a channel system resulting in confined valley-fill aggradational deposition, and, finally, relatively unconfined braided stream deposition. Only fluvial facies are recognized in outcrop in the Lake Cisco system; if Lake Cisco deltaic facies prograded through the area, the deltaic facies were later cannibalized by the subsequent fluvial system.

The sequence of events that can be interpreted from Lake Cisco facies indicates 1) that the low-gradient meandering system shifted basinward with delta progradation; 2) that eventual over-extension of the system may have resulted in stream avulsion and a new, more efficient, higher gradient stream course; and 3) that avulsion resulting in a higher gradient course could lead to progressive upstream incision of the fluvial channels seeking to adjust to the new profile of equilibrium. Valley erosion eventually reached equilibrium, followed by slow deposition in the valleys as the river gradually decreased its gradient by basinward progradation of its delta along its new course. Cycles of absolute and relative sea-level changes, as well as variations in basin subsidence and source-area uplift, are alternative factors that can also be invoked to explain depositional-erosional cycles such as exhibited by the Lake Cisco system.

Optional Locality G: Crevasse-Splay and Interdistributary-Bay Facies, Post-Ivan (King) Sandstone

Proximal crevasse-splay sandstone and mudstone originating from a large post-Ivan (King) distributary-channel system built northward and southward into flanking interdistributary bays or floodbasins. An upper delta-plain position is indicated by the absence of marine fossils. Locality G is a road cut along a graded county road 2.5 miles west of Texas Highway 67, about 2.5 miles northwest of Ivan, Stephens County, Texas (fig. 55). This locality has been previously described (Brown and others, Stop 2, 1969); local and regional maps are included in this earlier report.

The post-Ivan (King) deltaic system extends for many miles into the subsurface. In outcrop it is a high-constructive elongate system that displays thick channel-mouth bars, distributary channels, and thin delta-plain mudstones, sandstone, and coal beds (Locality H).

The splay at Locality G is composed of 10 to 15 feet of sandstone and mudstone that was rapidly deposited northward into the flanking flood basin or bay (fig. 13B). A series of cross-cutting, sandstone-filled splay channels are typified by normal and climbing ripple cross-laminations, moderate-scale trough cross-beds, and some contorted bedding. Distal splay deposits occur farther away from the distributary system to the north of Locality G. Each splay-channel-fill deposit may represent a single splay event; flow through the channels was low flow regime, but excessive bed-load sediment supply resulted in unusually thick ripple-drift cross-laminations.

Following splay deposition, thin coal deposits developed over the delta plain; upon abandonment, the delta was slowly transgressed by the Blach Ranch Limestone.

Optional Locality H: Bar-Finger Facies Displaying Diapiric Intrusions, Post-Ivan (King) Sandstone

Bar-finger sandstones of the post-Ivan (King) delta system are composed of thick superposed channel-mouth bars and distributary-channel-fill deposits; the high-constructive elongate deltas display intense sandstone deformation resulting from compaction and diapiric intrusion. Although bar-finger sandstones are found in other Cisco sandstones (e.g., Avis, Gonzales Creek), this deposit is exceptionally well exposed on the east side of the Clear Fork of the Brazos River, about 7.5 miles southwest of Eliasville, in northern Stephens County, Texas. The locality is on the Pete Reid ranch on the east side of the river, where an incised meander cuts the post-Ivan Sandstone (Brown and others, p. 56, 57, 1969) to form high bluffs; a deep, westward trending ravine exposes the bar-finger sand where its internal character can be easily observed.

The narrow, elongate sandstone, 35 to 45 feet thick, can be traced in outcrop for 8 miles before it enters the subsurface at the Clear Fork of the Brazos. The local geologic setting has been described (Brown and others, p. 56, 57, 1969).

The bar-finger sandstone is extensively deformed by subsidence and by injection of sandstone diapirs. Only rare horizontal laminations are preserved; large troughs or scour channels are folded and overturned. It is postulated that this bar finger formed much like the Mississippi birdfoot deposits described by Fisk (1961); that is, channel-mouth bars of high-constructive elongate deltas subsided into subjacent, highly water-saturated prodelta clays, with consequent vertical accretion or stacking of highly deformed delta-front facies (figs. 13B, 17, 18).

The bar-finger facies at Locality H is overlain by delta-plain mudstones containing thin calcareous lake deposits, thin destructional sheet sandstones, and a thin coal bed; the oldest Texas amphibian comes from this delta-plain facies. The delta-plain facies was transgressed by the Blach Ranch Limestone. Vertical sequences within high-constructive elongate deltas (fig. 20A) in a cratonic basin closely resemble the modern Mississippi birdfoot delta and other ancient analogs. The following section was measured at Locality H:

Top

5. Blach Ranch Limestone . . . . 2 feet
   Regional shelf-transgressive facies.
4. Clay containing thin coal, amphibians . . 15 feet
   Destructional marsh-bay facies.
3. Clay and sandstone . . . . 30 feet
   Local distributary-channel-fill sandstones 5 to 10 feet thick; thin fresh-water limestones and calcareous clays (6 inches), and thin sheet sandstones (1 to 2 feet) occur within the interval. Sandstone increases near the base. Delta-plain facies complex.
2. Sandstone, massive, highly contorted . . . . 35-45 feet

Near the top are preserved highly distorted scour channels representing bar-crest scour. Near the base are compactional and diapiric structures. This sandstone is elongate, and trends almost east-west. The stratigraphic position of the Ivan Limestone is 10 feet below the top of the sandstone; it is uncertain whether the limestone was eroded or squeezed from beneath the sandstone mass.

1. Mudstone, sandstones, and sandy limestones .... 20 feet+
Thin, post-Avis sandstone destructional bars; contain burrows, coral fragments; destructional facies of subjacent Avis delta.

Bar-finger sandstones typify high-constructive delta systems in the Cisco of North-Central Texas. Critical in their formation is a high mud-to-sand ratio, even though total thickness of the cratonic-basin deltaic facies may be small when compared to similar facies within more actively subsiding basins. Bar-finger sandstones and channel-mouth bars that display growth faulting provide interesting contrasts; in the former, delta-front facies fail and subside plastically, displacing underlying mudstones; the latter display greater competence and fail by gradual growth faulting.

Optional Locality I: Delta-Front and Proximal Prodelta Facies, Avis Sandstone and Wayland Shale

Rapidly deposited delta-front facies, subjacent (distal) flow rolls, and plant-rich prodelta mudstone provide insight into the delta-front/prodelta transition in a high-constructive lobate delta. Locality I is located in a road cut and in an adjacent railroad cut along Farm Road 701 about 1.4 miles south of Eliasville, in northernmost Stephens County, Texas (fig. 55). This portion of the facies tract is rarely exposed along the Cisco outcrop. Delta-front sandstones are part of the Avis Sandstone; prodelta mudstones compose the upper part of the Wayland Shale (fig. 41).

This locality was described earlier (Brown and others, p. 55-57, 1969). Locality I is stratigraphically and depositionally similar to Locality 9, except that the proximal prodelta facies is better exposed. Prodelta mudstones contain abundant macerated plant material; they become sandy and silty upward. Highly contorted flow rolls and other compactional features are well exposed in the road cut. Distal delta-front sandstones rarely contain normal ripple cross-laminations; they commonly exhibit horizontal laminations. One bed contains an unusual variety of ripple-drift cross-laminations that climb almost vertically (Walker, 1963). These ripple-drift structures point to exceedingly high rates of sediment input to the distal bar, probably during peak discharge. Flame structures occur locally within a more steeply dipping (probably growth-fault controlled) delta-front block in an adjacent abandoned railroad cut.

Within this small lobate Avis-Wayland delta, deposition on the distal channel-mouth bar was within high flow regime (horizontally laminated) or locally, deposition from suspension; flame structures and high-angle ripple-drift cross-laminations indicate high rates of sedimentation. Tilted sandstones (railroad cut) probably rotated along slump faults. The upper surface of the delta-front sandstones exhibits wave-oscillation ripples that developed after delta abandonment.

In the vicinity of Locality I (0.5-mile south of Eliasville on Farm Road 701), massive, highly contorted Avis channel-mouth bars up to 15 feet thick developed along the principal Avis distributary system; the occurrence of both bar-finger sandstones and growth-faulted lobate sandstones within the same system is significant. Continued reoccupation and progradation of principal distributaries led to significant subsidence and storage of thick bar-finger sands, while small, briefly occupied lobes underwent gradual growth faulting. Differences in delta-front geometry and compactional history apparently reflect the degree and duration of distributary-channel discharge.

Several such lobes are superposed in this region; following final Avis deltation, quartzose to calcareous destructional bars developed along the periphery of the delta lobes; destructional bars are highly burrowed. Ivan Limestone eventually transgressed the Avis system.

Optional Locality J: Confined Valley-Fill Fluvial Facies, Kisinger Sandstone

Large trough-cross-bedded conglomeratic sandstones within the Kisinger channel system exhibit strong unidirectional orientation that typifies confined flow within fluvial channels. Locality J occurs in the bed of Connor Creek, on the south side of Texas Highway 16, about 7.5 miles southeast of Graham, Young County, Texas (fig. 5, 74). The Kisinger channel system (fig. 41) underlies the Salem School Limestone and cuts the Home Creek Limestone. The channel is principally filled with sandstone and conglomerate; the upper part of the channel is filled with fissile, plant-rich mudstone, probably deposited after final channel abandonment. The Kisinger channel extends southwestward into the subsurface (Lee, 1938); its surface distribution can best be mapped by tracing its erosional contact with the underlying Home Creek Limestone (fig. 74).

Orientation of large- to moderate-scale trough cross-beds at Locality J uniformly point to the southwest, and, therefore, substantiate channel orientation based on mapping. The channel was relatively straight and deep. Erosion extended through 30 to 40 feet of Home Creek Limestone and almost 75 feet of underlying Colony Creek Shale; basal Kisinger gravels may locally cut the upper part of the Ranger Limestone (Lee, fig. 2, 1938).

Although a detailed study of the Kisinger system has not been completed, it appears to fit a valley-fill model similar to that shown in figure 14. For many years, geologists have pointed to the Kisinger channel as evidence of a regional unconformity at the top of the Missouri (Canyon) Series throughout Texas. Channeling in the vicinity of Locality J is the only known occurrence in North-Central Texas. Extensive surface and subsurface mapping in the region indicates a conformable relationship between Missouri and Virgil strata everywhere but along the incised Kisinger channel system. Wedged between the Home Creek Limestone and its uppermost tongue, the Salem School Limestone (fig. 41), the Kisinger channel was cut into marine shelf deposits; upon abandonment, fine sediment was deposited in a brackish- or fresh-water-filled channel course that trapped thick beds of plant debris. Until further work delineates its subsurface extent and other factors involving internal compositional variations, its genesis must remain speculative. Its unique occurrence, however, makes simple sea-level or tectonic control questionable.

Locality 12: Interdistributary-Embayment and Superposed Distributary-Channel-Fill Facies, Gonzales Creek Sandstone

Significance and location.—Distributary-channel-fill sandstones are superimposed upon brackish-water, interdistributary-bay mudstones, burrowed sandstones, and localized limestone shoals (fig. 75) near the top of the Gonzales Creek Sandstone. Underlying bar-finger sandstones (not well exposed at this locality) rest upon thick prodelta facies (Finis Shale) of the high-constructive elongate delta system (fig. 13). One distributary-channel-fill deposit has been highly deformed, probably by compactional subsidence and diapiric intrusion. Inferred splay deposits apparently entered the interdistributary bay from an adjacent distributary. An abandoned, mud-filled channel cuts into the top of the distributary-fill facies. Locality 12 is a road cut along Texas Highway 16, about 5 miles southeast of Graham, Young County, Texas (figs. 55, 74). The internal character of the distributary-channel-fill sandstones, and their stratigraphic relationship to the bay facies, make the locality of particular interest. The complex nature of the internally deformed channel-fill sandstone is uniquely exposed in the road cuts.

Local and regional stratigraphic setting.—The Gonzales Creek Sandstone supports bluff exposures along most of its outcrop in North-Central Texas (fig. 74). The sandstone system extends many miles westward into the subsurface (fig. 47) along a beltlike complex of dip-oriented sandstone bodies.

The Gonzales Creek Sandstone overlies relatively thick mudstone and thin sandstone beds of the Finis Shale; the lenticular, sandy Gonzales Limestone occurs locally at the top of the Finis Shale and is overlain, where present, by the Gonzales Sandstone (fig. 41). Although the base of the Gonzales Sandstone sequence is conformable in many areas, fluvial channels locally cut through the underlying Gonzales Limestone and uppermost Finis Shale. These channel-fill deposits are conglomeratic and resemble other channel-fill conglomerates throughout the Cisco (e.g., Avis, Lake Cisco). The Gonzales Limestone locally shoals out into uppermost Finis or lowermost Gonzales Creek sandstones; this pinch-out may be confused with erosion of the limestone.

Overlying the sequence of Gonzales Creek Sandstones is a mudstone (Gonzales Creek Shale, fig. 74) composed dominantly of interdistributary-bay mudstones that grade upward into extensive, sheetlike delta-destructional sandstones with oscillation ripples and burrows on upper surfaces, and capped by the regionally extensive Bunger Limestone.

The Gonzales Creek Sandstone is, therefore, a complex of sandstone and mudstone units that includes most deltaic facies (fig. 15B, 20A): thick delta-front and channel-mouth-bar sandstones, distributary-channel-fill sandstones, and splay deposits that are part of initial Cisco progradation in North-Central Texas. The interval between the Home Creek and Bunger Limestone represents a principal episode of delta-building, abandonment, and destruction.

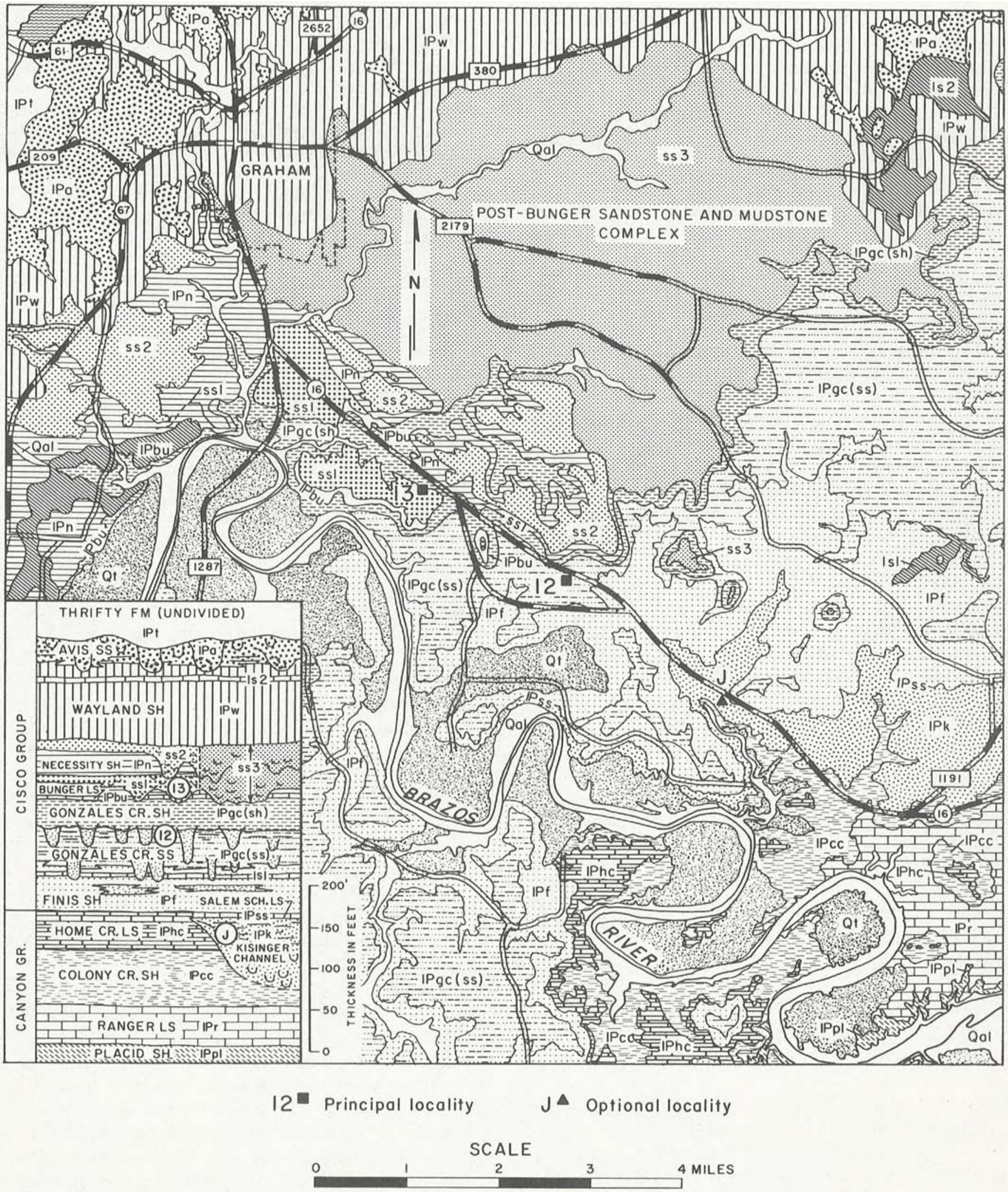

Figure 74. Geologic map, lower part of Cisco Group, Graham area, North-Central Texas. Numbers refer to field localities. Mapping by T. H. Waller; modified by L. F. Brown, Jr.

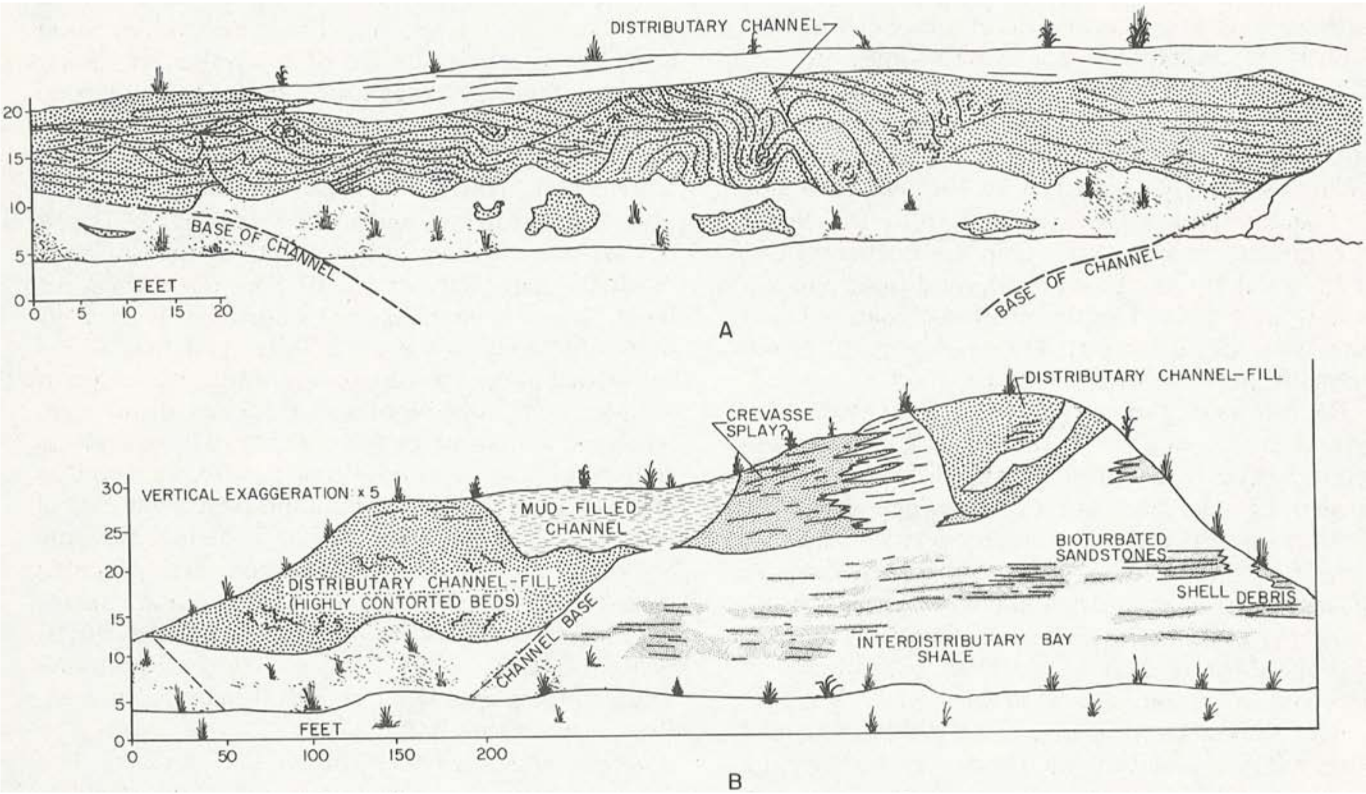

Figure 75. Field locality 12: Distributary-channel-fill and interdistributary-bay facies, Gonzales Creek Sandstone, along Texas Highway 16 about 5 miles southeast of Graham, Texas. See figs. 55, 74 for location. A. Highly contorted distributary-channel-fill sandstones on south side of road displaying folds and faults. B. Highly exaggerated, schematic view of entire south road cut, showing variety of delta-plain facies.

Facies composition and inferred depositional processes.—Facies exposed at Locality 12 (fig. 75) can be grouped into three principal categories: 1) interdistributary-bay mudstone, sandstone, and limestone; 2) distributary-channel-fill sandstones; and 3) inferred crevasse-splay and abandoned channel deposits (figs. 13, 17).

Interdistributary-bay mudstones (fig. 75B) contain some plant fragments and are gray, locally sandy and silty clays with zones 2 to 4 feet thick composed of intercalated sandstones and mudstones; individual sandstone beds several inches thick are burrowed and display wave ripples and ripple laminations. Thin-bedded sandstones locally grade laterally into massive, ripple cross-laminated, burrowed sandstone; these shoals or bars containing fossil fragments locally grade into sandy, bioclastic limestone. Feeding trails are abundant at the base of interdistributary sandstones. These mudstones, except where cut by distributary channels, grade upward into extensive marine sandstones that directly underlie the Bunger Limestone; the destructional and strand-plain facies are exposed in road cuts along Highway 16 between Localities 12 and 13 (fig. 74).

Two inferred distributary-channel-fill bodies are exposed at Locality 12. An upper channel occurs in the northwest end of the road cut and a lower channel is exposed in the southeast end of the road cut (fig. 75B); the base of the lower, highly deformed channel fill occurs below road level (fig. 75A). The less deformed, upper distributary-channel fill (northwest end of cut) contains trough cross-beds, wood casts, and clay chips (fig. 15B); sands are fine- to medium-grained. The highly deformed distributary-channel-fill sandstone (southeast end of cut) is also a fine- to medium-grained unit that contains clay chips and wood; trough cross-beds are visible, but much of the internal character has been obscured by soft-sediment faulting and folding. Diapiric sand intrusions (fig. 18) are thought to account for much of the deformation; the base of the channel in the road cut clearly erodes the interdistributary facies (fig. 15B), but the nature of the sandstone beneath the level of the road cut is, naturally, speculative. It is possible that the lower channel may be superimposed upon an underlying channel-mouth bar (fig. 13A). Such Gonzales Creek bar-finger sands (Fisk, 1961) have been observed in the region.

Another small sandstone body within the cut represents either another distributary-channel-fill deposit or, more likely, a crevasse-splay deposit (fig. 75B). Splay origin is suggested by inclined beds that exhibit accretion eastward and aggradation within the interdistributary facies. The inclined beds (best observed on the northeast side of the road) may have splayed from the upper distributary channel exposed in the northwest end of the road cut. An abandoned, mud-filled channel that is well defined in the northeast road cut also cuts into the lower distributary-channel-fill sandstone on the southwest side of the road.

Depositional summary.—An early Cisco delta system in the vicinity of Locality 12 is composed upward of 1) Finis prodelta and distal delta-front facies; 2) Gonzales Creek bar-finger deposits (channel-mouth bars, distributary channels), delta-plain facies (small distributary channels, crevasse splays and interdistributary-bay mudstones, burrowed sandstones, and sandy limestone shoals); 3) delta-destructional mudstones, burrowed and wave-rippled strandline sandstones; and 4) marine Bunger Limestone (fig. 20A). The highly deformed distributary-channel-fill sandstones at Locality 12 are predictable within high-constructive elongate delta systems, especially those that prograded over thick prodelta facies such as the Finis Shale. Elsewhere along outcrop, for example to the northeast in the area of the outcrop of sandstone 3 (fig. 74), thick gravel-filled fluvial channels originating at about the stratigraphic position of Locality 12 cut out the deltaic facies and rest on Finis Shale. These gravel-filled channels supplied Gonzales Creek deltas tens of miles to west; their incision and subsequent aggradation is similar to that described for the Lake Cisco Sandstone (Locality 11) and at Locality 13. Deltaic facies like those exposed at Locality 12 are preserved along outcrop and in the shallow subsurface in areas between the principal fluvial channels that supplied distant Gonzales deltas (fig. 47).

Locality 13: Trough-Cross-Bedded Facies Deposited Under Confined Channel Flow, Post-Bunger (McMillan) Sandstone

Significance and location.—Conglomeratic sandstones deposited under confined flow within incised fluvial channels and small valleys are predominantly large-scale trough-cross-bedded sequences that become finer upward in grain size and in scale of sedimentary structures (fig. 76). Locality 13 is in a road cut along Texas Highway 16, about 4 miles southeast of Graham, Young County, Texas (figs. 55, 74). This well-exposed sequence is representative of a number of similar fluvial facies throughout the Cisco Group (Localities 11, J). These valley-fill sequences (fig. 14) are generally restricted to upper delta-plain and alluvial-plain settings and are concentrated in the present outcrop belt and shallow subsurface. Depth of erosion averages about 30 feet, although channels may cut 50 to 80 feet into subjacent beds. The Kisinger channel (Locality J) displays unusually deep scour of 100 to 150 feet. Cisco rocks that crop out progressively up paleoslope in Young, Jack, and Montague Counties display extensive channel-fill conglomerates. These systems reflect shifts in base level that resulted in development of new profiles of equilibrium for the fluvial system; eustatic sea-level adjustment, tectonic activity, and/or stream evolution are probable causes. Locality 13 occurs on the southern fringe of a classic multistory sequence of such fluvial systems (Lee, 1938); these cyclic erosional-aggradational episodes are well developed in post-Bunger sandstone 3 (fig. 74).

Local and regional stratigraphic setting.—The conglomeratic facies at Locality 13 (sandstone 1, fig. 74) is one of several such superposed systems that occur within the Cisco Group of Young County. The belt of conglomeratic channel-fill systems extends westward into the subsurface. Limestones either pinch out or are cut by channels within this belt (fig. 41, 74). Throughout the Cisco outcrop belt, these kinds of fluvial systems become progressively more common higher in the group (fig. 46A); deltaic facies that are common in outcrop in the lower Cisco (fig. 46B) are increasingly cannibalized by channel erosion in higher Cisco units. The upward shift from dominantly deltaic to fluvial clastic facies in outcrop is, in part, explained by the westward shift of fluvial systems as the basin was gradually filled.

The post-Bunger sandstone at Locality 13 (sandstone 1, fig. 74) cuts the Bunger Limestone repeatedly north of the Brazos River; northward, the conglomeratic sandstone merges with other post-Bunger channel-fill deposits to form the "post-Bunger cycles" of Lee (1938) that have been grouped into a single map unit (sandstone 3, fig. 74). Open-marine conditions returned to the area between fluvial depositional episodes as shown by the presence of highly eroded limestone beds within the fluvial belt.

Regionally, the post-Bunger—pre-Gunsight sequence of superposed fluvial sandstones and

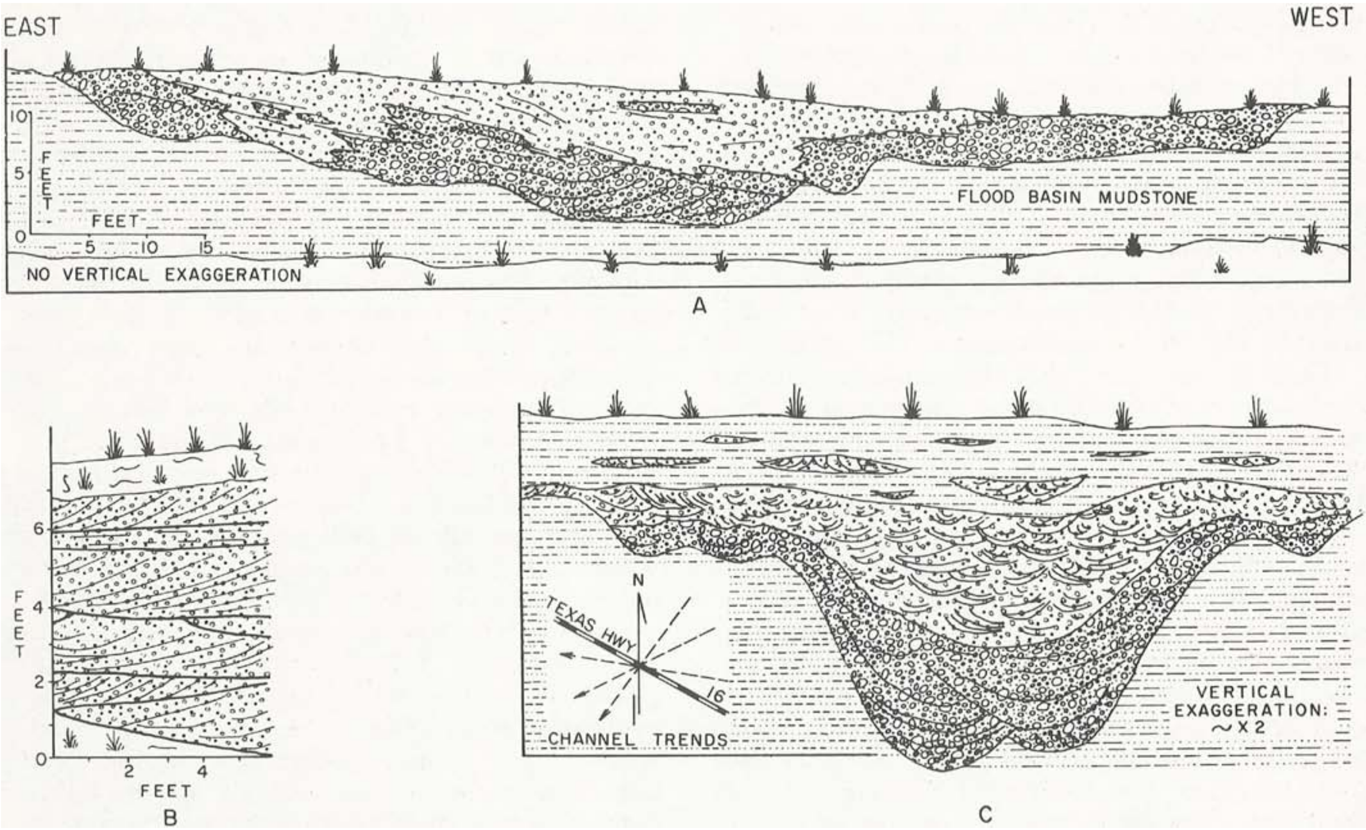

Figure 76. Field locality 13: Post-Bunger valley-fill facies, along Texas Highway 16, about 4 miles southeast of Graham, Texas. See figs. 55, 74 for location. A. Gravel-filled troughs and channels, confined basal valley-fill facies, south side of road. B. Large-scale trough cross-beds, less confined upper valley-fill facies, north side of road. C. Composite, idealized valley-fill model showing orientation of post-Bunger channel axes.

conglomerates extends basinward to join a series of beltlike systems that extend westward along paleoslope (fig. 48). Vast quantities of terrigenous sediment that passed through these upslope fluvial systems supplied deltaic and slope systems far to the west.

Facies composition and inferred depositional processes.—Channel-fill facies at Locality 13 (fig. 76) display a general upward fining sequence. Large-scale conglomerate-filled trough cross-beds predominate in basal, highly confined channels (fig. 76A); smaller, trough-cross-bedded sandstones are common in higher, less confined parts of the channels (fig. 76B). Depth of channel scour at Locality 13 is uncertain, but it was at least 45 feet; the top of the road cut is approximately at the stratigraphic position of the Bunger Limestone. In the next road cut on Texas Highway 16 east of Locality 13, the Bunger Limestone is directly overlain by sandstone 1 (fig. 74). Mudstones may fill uppermost parts of channels, probably after abandonment. In other areas, estuarine mudstones have been observed in upper channel-fill; plant-rich fissile shales fill the upper part of the Kisinger channel (Locality J).

Flow in the channels at Locality 13 was dominantly westward as indicated by persistently unimodal cross-bedding. Channel-fill ranges from 1- to 2-inch-diameter chert pebbles in some basal troughs, to coarse- and medium-grained sandstone in upper channel fill (fig. 14). Wood fragments (*Calamites*) occur within the sequence.

Flow in the channels was transitional between high and low regime; washouts and migrating transverse bars account for the observed trough cross-beds. Discharge in the highly confined basal part of the channels was exceedingly high with sufficient competence to cause migration of gravel bars up to 3 feet high. Although there was little change in flow regime during channel aggradation, the caliber of sediment and the scale of the bars and washouts diminished upward with less channel confinement and diminishing water depth (fig. 14A, B).

Depositional summary.—Valley-fill deposits, such as those exposed at Locality 13, were deposited under an aggradational regime within incised channels (fig. 14A). Flow was confined by channel width; flow was transitional between low and high regime. Deposition was in the form of migrating transverse gravel bars that gave way upward to sand bars, resulting in unimodal trough cross-beds. Upward diminishing confinement and water depth account for upward fining of grain size and decreasing scale of sedimentary structures. Sediments from suspension deposition and concentration of organic matter may fill uppermost channels following abandonment.

Control for the degradational-aggradational cycles lies with one or more interrelated factors that aperiodically changed base level. Eustatic or relative sea-level changes of a minor magnitude or tectonic adjustments in the basin and source area provide popular explanations. Careful consideration should also be given to changes in gradient of stream systems shifting by avulsion from overextended courses (feeding basinward deltas) to short, high-gradient courses. In response, streams may have eroded to adjust to a new profile of equilibrium; eventually, delta progradation again led toward overextension with decreasing gradients that flattened the profile of the stream and resulted in alluviation that migrated upstream.

Locality 14: Thin Strand-Plain Facies and Associated Brackish-Water-Bay and Lagoonal Coals, Harpersville Formation

Significance and location.—Repetitive sequences of distinctive clays, sub-bituminous coals, and thin sheetlike marine sandstones are unusually well developed within interdeltaic embayments of the Harpersville Formation (fig. 78). These broad embayments developed between principal fluvial-deltaic systems throughout Cisco deposition, but this depositional setting became most prominent during deposition of the Harpersville Formation. The precise location of embayments shifted (figs. 50, 51), but their genetic relationship to adjacent deltaic systems (fig. 22) remained a key factor in explaining their distribution and facies composition.

Locality 14 is located in a small excavated pit on the north side of a graded county road, 0.7-mile west of Texas Highway 16, 1.5 miles south of its intersection with Texas Highway 199 at Loving, Young County, Texas (figs. 55, 77). Facies at this locality occur within an interdeltaic embayment in the lower part of the Harpersville Formation between the Breckenridge and the Crystal Falls Limestones (=Upper Hope Sandstone). Nearby towns of Newcastle and Loving were coal-mining centers in the late 19th century when Harpersville coals were mined for several decades. Throughout much of North-Central Texas, the Harpersville Formation was prospected and mined, locally at such places as Crystal Falls, Carbondale, Newcastle, and Loving. Locality 14 provides a relatively typical example of these coals; five or six such superposed occurrences may occur within the 200 to 250 feet of Harpersville rocks. Cyclicity recognized within the Harpersville embayments is coincident with stages of deltaic development in contemporaneous delta systems. The depositional setting of Locality 14 is somewhat similar to that of Locality 10; although sandstones are thin, the strand-plain facies are well developed at Locality 14. The best developed embayment sequences within the Cisco Group are related to the Cook deltaic system (fig. 50).

Local and regional stratigraphic setting.—Locality 14 (fig. 78C) occurs south of and stratigraphically equivalent to a post-Breckenridge—pre-Crystal Falls deltaic lobe (Upper Hope Sandstone). The lowermost Harpersville claystones and thin sheet sandstones crop out (fig. 77) in a flat to slightly rolling belt beneath mesas capped by overlying Harpersville fluvial sandstones (figs. 50, 51). Most coal beds in the Newcastle and Loving areas developed within the broad Upper Hope interdeltaic embayment; other important coals occur in the more restricted Cook interdeltaic embayments in southwestern Young County (fig. 50). Regional strike of the Cisco Group changes significantly in central Young County; a strike of N 21° E in Eastland, Stephens, and southern Young Counties shifts 40 degrees to N 61° E in eastern Young and Jack Counties.

Facies composition and inferred depositional processes.—The sequence exposed at Locality 14 (fig. 78B) consists of basal gray, unfossiliferous claystones containing septarian nodules and composed principally of mixed-layer clays and kaolinite; the top of the basal unit directly beneath the lower coal has a high kaolinite content with a moderate amount of illite. Two coal beds are separated by dark, fissile, plant-rich shales. Jarosite is common as seams and dikes in both coals and the plant-rich shale; selenite is common on weathered shale surfaces. Above the uppermost coal lies a moderately fissile, dark gray shale containing plant fragments, jarosite, and selenite; composition is principally illite with minor kaolinite. The upper sandstone sequence is composed of

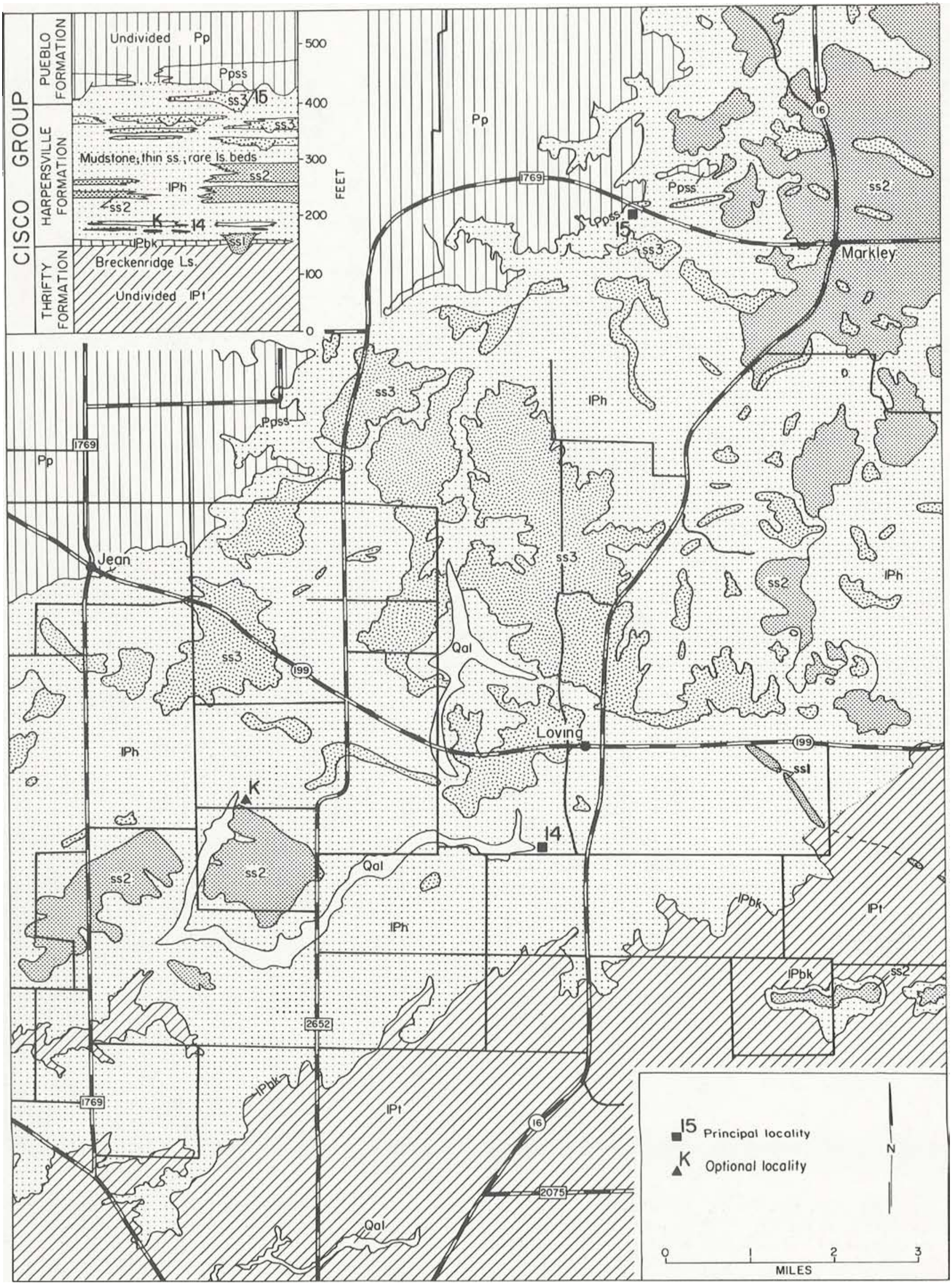

Figure 77. Geologic map, middle part of Cisco Group, Loving area, North-Central Texas. Numbers refer to field localities. Mapping by W. E. Galloway; modified by L. F. Brown, Jr.

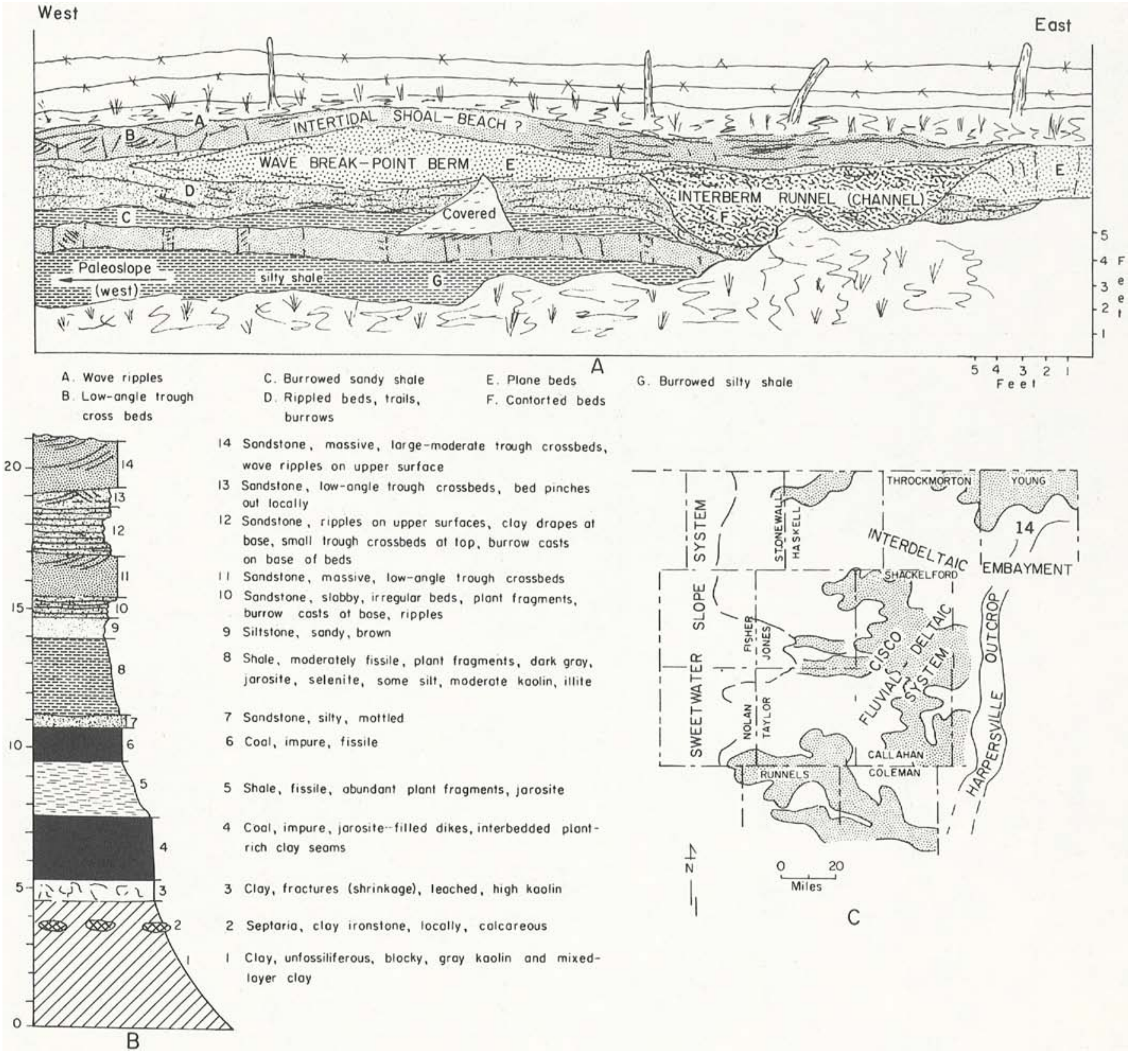

Figure 78. Field localities 14, K: Interdeltaic-embayment facies, lower part of Harpersville Formation, southwest of Loving, Texas. See figs. 55, 77 for location. A. Strike-fed beach or berm, interdeltaic-embayment facies at Optional Locality K along graded road about 4 miles southwest of Loving. B. Measured section at quarry, Locality 14, along graded road 1.5 miles south of Loving, showing coal beds and strike-fed sandstones. C. Regional facies map showing location of (Upper Hope Sandstone) interdeltaic area.

fine- to medium-grained sand occurring as massive sandstone beds about 2 feet thick displaying shallow moderate-scale trough cross-beds and wave ripples on upper surfaces; and as thin-bedded, ripple cross-laminated, bioturbated beds.

At Locality K (fig. 78A), a more extensive exposure of the sandstone facies points to a strandline origin based on probable beach or shallow, subaqueous berm and runnel sandstones that appear to have accreted westward or basinward. Variations of the sequence at Localities 14 and K occur in superposed sequences within interdeltaic embayments (Brown, fig. 7, 1960; Galloway and Brown, figs. 17, 18, 1972).

Depositional summary.—Interdeltaic embayments are filled with superposed, repetitive sequences of mudstones, claystones, coals, thin sheet sandstones, and brackish-water limestones that can be tied genetically to contemporaneous deltaic-fluvial depositional cycles and delta-destructional cycles (fig. 22). Sediment transported from delta distributaries laterally along strandline by longshore drift entered these embayments and was deposited within a variety of environments—in delta-flank basins, along mud-rich chenier coastlines associated with tidal flats, along thin strand plains and barriers, and within bays or lagoons where the terrigenous facies intertongue with brackish-water limestones (fig. 21). Field studies show that principal longshore drift in the Cisco was counterclockwise or to the south on the eastern flank of the basin. Locality 14 was principally supplied from the small Upper Hope delta that lay to the north (fig. 78C).

During active delta progradation, and especially in parts of the embayment nearest sediment supply, mud-rich deposits dominate the section. Reworking of strike-fed sediment, much like along the Louisiana chenier coastline (Gould and McFarlan, 1959), may account for many of the thin Harpersville strand-plain sandstones within thick coal and mudstone sequences.

Many of the sequences such as at Locality 14 probably represent shallow, brackish lagoons situated landward of thin beach ridges that developed following deltaic abandonment as foundered deltas were reworked. Such units might be called transgressive barriers, but they apparently developed and briefly accreted basinward as normal winnowing and storms locally supplied sand. Continued compaction of the mud-rich coastline eventually resulted in submergence; a new line of berms then developed landward and another short-lived barrier-lagoon system was developed. The coal beds at Locality 14 were probably deposited behind a barrier-strand plain that is located several miles basinward; the beach berms at Locality 14 are inferred to be contemporaneous with the coal beds to the east (landward).

Optional Locality K: Break-Point or Storm Beach Berm and Runnel Facies, Harpersville Formation

Inferred beach berms and associated runnel-fill sandstones display basinward accretion along a graded county road 0.8-mile west of Farm Road 2652, 1.5 miles south of its intersection with Texas Highway 99, approximately 2.5 miles due southeast of Jean, Young County, Texas (figs. 55, 77). Exposed for about 120 feet along a road at the east end of a bridge over Oak Creek, the sandstone at Locality K is approximately equivalent to the sandstone at Locality 14, 5 miles to the east. Thin, burrowed, ripple cross-laminated sandstone beds several inches thick are overlain by lenticular sandstones about 2 feet thick with horizontal bases and convex upper surfaces. A massive sheetlike sandstone about 1.5 feet thick that overlies the berms may represent thin storm-washover sandstones. A small channel-fill deposit about 3 feet thick parallels the principal berm on its landward (east) side. Two such berms exposed at Locality K show evidence of westward (basinward) accretion. Upper surfaces of the unit exhibit wave-oscillation ripples.

The local and regional stratigraphic setting for Locality K is similar to that for Locality 14. The locality provides insight into the internal character of the sheetlike marine sandstones that compose a small part of interdeltaic embayment deposits. It also clearly demonstrates that so-called sheet sandstones or shelf sandstones of many workers are not uniform, internally consistent facies, but are composed of complex accretionary internal facies.

Locality 15: Fine-Grained Meanderbelt Facies, Uppermost Harpersville Formation

Significance and location.—A series of superposed point bars in the uppermost Harpersville Formation (Bluff Creek Sandstone) displays the classic internal geometry and spatial distribution of sedimentary structures in fine-grained meanderbelt deposits (fig. 79). Exceptional exposures of Cisco fine-grained-meanderbelt facies occur in the vicinity of Locality 15, along Farm Road 1769, 2.5 miles west of its intersection with Texas Highway 16 at Markley, Young County, Texas (figs. 55, 77).

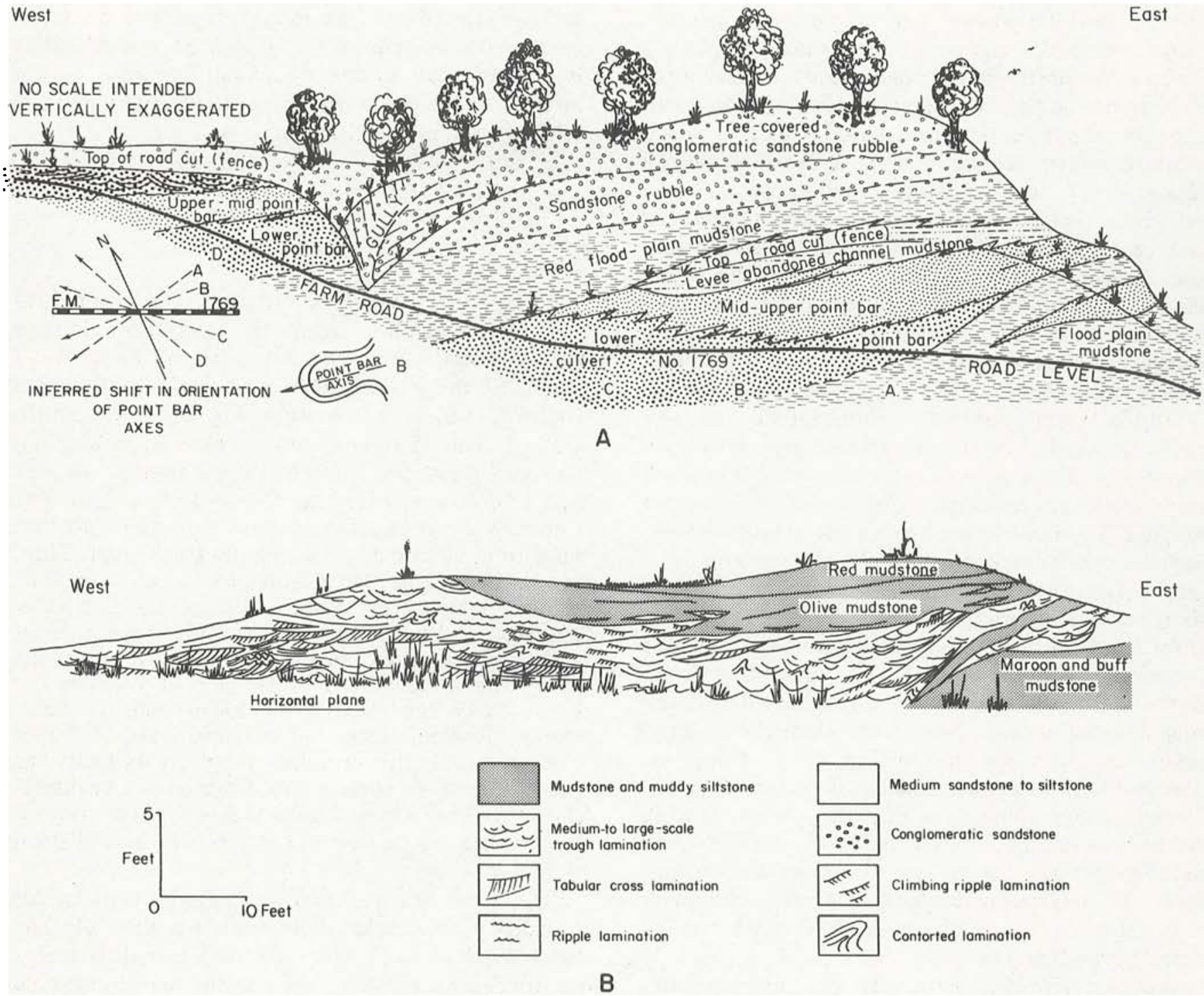

Figure 79. Field locality 15: Fine-grained meanderbelt facies, upper part of Harpersville Formation (Bluff Creek Sandstone), along Farm Road 1769, about 2.5 miles west of Markley, Texas. See figs. 55, 77 for location. A. Schematic view (north) of superposed point bars and overbank mudstones with inferred shift in point-bar axes. B. Internal characteristics of fining-upward point-bar sandstones. Adapted from Galloway and Brown (1972).

The bars fine upward in grain size and in scale of sedimentary structures (figs. 12, 15D). At least two episodes of point-bar development occurred at Locality 15; the meanderbelt is overlain by fluvial conglomerates. Flood-plain mudstones are also well exposed in the valley of Brushy Creek. These uppermost Harpersville (Bluff Creek) fluvial sandstone bodies provide an excellent opportunity to study the internal anatomy of a meanderbelt.

Local and regional stratigraphic setting.—The Bluff Creek Sandstone (sandstone 3, fig. 77) is exceptionally well exposed along broad dip slopes in northern Young County. Because of the change in regional dip from west to northwest, coupled with the occurrence of a structural high along the Jack-Young County line and a divide between Brazos and Trinity drainage, dip slopes in northern Young and northwestern Jack Counties are unusually broad. With Cisco paleoslope (and elongate sandstones) trending east-west and with very low dips to the northwest, elongate meanderbelt sandstones are exposed for as much as 8 miles along a dip direction (Galloway and Brown, 1972, 1973). Flood-plain mudstones erode readily to expose elongate meanderbelts that trend east-west along paleoslope; these exhumed sandstones can be seen on the geologic map of the area (fig. 77).

The meanderbelt sandstone at Locality 15 is part of the Bluff Creek fluvial system that extends westward for many miles into the subsurface (fig. 51). The fluvial system supplied sediment to deltas that terminated in Shackelford, Jones, and Haskell Counties.

Facies composition and inferred depositional processes.—The lower of two point-bar sequences (fig. 79A) exposed in the road cut on the north side of the Farm Road 1769, displays lower, middle, and upper point-bar facies (fig. 79B). Large tabular foreset beds and some large- to moderate-scale trough-cross-bedded sandstones occur at road level, especially near the culvert that underlies the highway. The lower point-bar axis nearly parallels the highway so that large trough cross-beds probably occur below road level; it can be speculated that gravel-sized sediment representing channel lag may also occur beneath the level of the highway. A vertical sequence (fig. 15D) upward through the bar, or eastward up the inclined accretionary beds (figs. 12B) includes large tabular cross-beds and medium- to large-scale trough cross-beds (lower), medium- to small-scale trough cross-beds and tabular cross-beds (middle), and ripple and ripple-drift cross-laminations (upper). Siltstone and calcareous olive mudstone at the top of the point bar probably represent levee deposits; red and maroon mudstones above and below the bar are of flood-plain origin. The lower point-bar sandstones exhibit compactional deformation. A gradual shift in the point-bar axis (fig. 79A) can be recognized by the varied attitudes of accretional units; accretion of the bar was generally from east to west toward a shifting thalweg.

Following deposition of the lower point bar, the channel was abandoned and filled, at least in part, with mudstone. Following reoccupation of the channel course, another superposed point bar was deposited (fig. 79A). The upper bar resembles the lower, but the road cut exposes only the uppermost lower bar (large- to medium-scale trough cross-beds) with a bar axis that dips northwestward; the basal bar facies are buried north of the highway.

Large-scale conglomeratic trough cross-beds were deposited upon the meanderbelt facies, probably within a confined, valley-fill channel system. This coarse-grained system is probably post-Saddle Creek (Tannehill Sandstone).

Depositional summary.—A late Harpersville meandering stream, flowing westward at Locality 15, deposited two superposed point bars. Maximum water depth in the thalweg was probably little over 15 feet. Locality 15 was located on the east side of the stream course as it shifted westward into its cut bank. The channel was briefly abandoned, but upon reoccupation another bar was built with the shifting thalweg to the north of the highway. The narrow meanderbelt sandstone is a relatively straight to slightly sinuous body that is surrounded by red to maroon mudstone of overbank-flood-plain origin (fig. 12A). The fine-grained meanderbelt (Bluff Creek system, fig. 51) was cut by a later valley-fill fluvial system.

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